

Recent progress on proppant laboratory testing method: Characterisation, conductivity, transportation, and erosivity

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ABSTRACT

In hydraulic fracture, the choice of proppant is very crucial. It not only props the fractures in the formation but also maintains the fracture conductivity. Proppant technology is advancing rapidly with the advance in hydraulic fracture. Hence to ensure a more consistent proppant evaluation in the manufacturing of proppants, standardisation of proppant evaluation is imperative. The ISO and API have published several recommended practices for this purpose, but they are still lacking in many areas. This is because many theories underlying the performance of proppant have not been fully understood, such as the theory of proppant embedment and diagenesis, as well as their impact on proppant conductivity performance, which is the current focus of research in proppant studies. This is especially true with the high pace evolution of proppant technologies and thus requires updates from time to time. In addition to the recommended practices, different approaches had been explored in enhancing the way proppants are evaluated. This paper presents a short review of the modifications and improvements that have been proposed in the evaluation of proppant characteristics, conductivity, transportation, and erosion. The objectives of this review are to provide an overview of the current proppant testing practices, including the current standards' limitation and challenges as well as modifications and improvements that have been proposed to laboratory-based testing, including the area that needs to be explored further.

1. Introduction

Hydraulic fracturing (HF) is a method for enhancing oil and gas production where a large number of fractures are created to allow trapped oil or gas to move freely. According to Economides (2009), HF has been proven as a highly robust technology since its emergence in the 1950s. It improves the permeability of formation by breaking down rocks and forming fractures through the injection of fluids at sufficiently high pressure. The induced fractures are then kept open via proppant placement, which is pumped in the form of slurries.

Proppant, as defined in "The Schlumberger Oilfield Glossary" (1998), is particles at a certain size, typically between 8 and 140 mesh (106 μm –2.36 mm) (Liang et al., 2016), which is mixed with fracturing fluid in order to keep fractures open after an HF treatment. In HF, the choice of proppant is very important as it keeps the fracture open, allowing the production of hydrocarbons. The performance of the proppant is of utmost importance and is affected by many factors. This includes the properties of the proppant itself, the properties of the formation as well as the transportation system. Measuring the proppant

performance, prior to performing HF, can give advantages to the stimulation operation (Liang et al., 2016).

Currently, the industrial practice in measuring the characteristics and performance of proppant follows the standards that have been set by the International Organization for Standardisation (ISO) and the American Petroleum Institute (API). However, despite the established standards, many researchers are struggling to produce consistent results. For example, in terms of proppant conductivity, Blair (2015) found that the variation of results from a laboratory to another (that followed the current API standards) could be as much as 80% when the variations in the conductivity is set around 20% within each laboratory. This might be due to the lack of documentation on the statistical variation of some factors that affect the conductivity. Some of these factors includes variation in pack width, secondary changes in pack width and variation in permeability. In another study, Vincent (2009) found that the conductivity values in the field scenario may be less than 10% of the lab-measured values. The author attributed this to the unaccounted cumulative damage factors. Schubarth et al. (2006) and Liang et al. (2015) even stated that the net effect of factors that can cause the

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underperformance in the field, can result in up to 98% reduction in conductivity. These factors include non-Darcy or multiphase flow, fines plugging, proppant embedment, formation spalling, filter cake build-up and gel damage. In addition, the mechanisms of these factors, especially proppant embedment and proppant diagenesis that affects the conductivity, are still not fully understood. In fact, many researchers still trying to generate ways to model or recreate the phenomenon in a laboratory environment, such as the modelling by [Li et al. \(2015\)](#) and [LaFollette and Carman \(2010\)](#).

In addition, the recent advance in proppant technologies is leading to the emergence of new types of proppant, such as ultra-lightweight proppant, multifunctional proppant and proppants of different shapes ([Liang et al., 2015, 2016](#)). Some of the standards for measuring proppant performance may not be suitable for these proppants. To the best of the authors' knowledge, not many papers have been dedicated to solely reviewing in depth the laboratory testing procedures related to proppant quality and performance, namely the proppant characteristic testing, proppant conductivity and proppant erosion, despite the importance of understanding these procedures for accuracy and reproducibility. This is because many factors affecting proppant quality and performance are still not fully understood. Hence many studies are more focused on unveiling the theoretical knowledge instead. This is worsened by the increasing trends in mathematical and simulation modelling, such as the works done by [Wang et al. \(2019\)](#), [Chang et al. \(2017\)](#) and [Santos et al. \(2018\)](#), due to its time and cost-effectiveness. Moreover, there has been no comparative studies made on any of the newly proposed method or any modifications made in the few papers available that reviewed on the testing procedure, especially in terms of proppant conductivity testing standards, such as by [Duenckel et al. \(2016, 2017\)](#) and [Kaufman et al. \(2007\)](#). Thus, this paper will focus on the review of proppant characterisation and performance testing; the standards, the alternative, limitations, and challenges.

2. Proppant evolution

2.1. Basic types

During the emergence of HF in the 1950s, sand was typically used as proppant, with the two most widely used being the Ottawa Sand and Brady Sands ([Economides, 2009](#)). While sand is the cheapest proppant as it is available in abundance in nature, it has a low strength. Sand is only able to withstand pressure up to 6000 psi, which usually occurs at depth of about 8000 ft ([Economides, 2009](#); [Liang et al., 2016](#)).

In 1979, the first generation of ceramic proppant was introduced into the market by Exxon Production Research ([Economides, 2009](#)). The emergence was the result of the increase in the need for higher strength proppant due to the exploration of deep gas reservoir in the 1970s. The ceramic proppant was made from bauxite. As affirmed by [Liang et al. \(2015\)](#) and [Economides \(2009\)](#), ceramic proppant is greatly superior to sand proppant in terms of its capability in withstanding high closure stresses, which is as high as 10,000 psi. In addition, being man-made, ceramic proppant is also more uniform in size and shape, with higher sphericity and roundness, which leads to better formation conductivity ([Economides, 2009](#)). Despite having a more costly production, ceramic proppant is sought for its high thermal and chemical stability ([Economides, 2009](#); [Liang et al., 2015](#)).

In general, the ceramic proppant can be classified into three main categories; lightweight ceramic (LWC), intermediate density ceramic (IDC) and high density ceramic (HDC) ([Liang et al., 2015, 2016](#)). These categories are based on the content of alumina, as it is directly proportional to the strength and density of ceramic proppant. However, the high quality of ceramic grain needs to be maintained and the internal porosity should be minimised during the manufacturing process to ensure the strength of the ceramic proppant ([Liang et al., 2016](#)). In general, the alumina content of LWC, IDC and HDC are 45–50%, 70–75% and 80–85%, respectively. However, it is interesting to note

that [Palisch et al. \(2015\)](#), in their pursuit of ultrahigh-strength proppant (UHSP), found that increasing alumina content does not always increase the density and strength of ceramic proppant. In their experiment, the increment of the alumina content to nearly 100% did not yield the desired increase in the aforementioned properties of the proppant due to limitations of the manufacturing process.

Apart from utilising ceramic proppant for deeper well application (above 8000 ft), the quality of proppant can be enhanced by encapsulating the proppant with resin coating. This type of proppant is called resin coated proppant ([Economides, 2009](#)). Epoxy resins, furan, polyesters, vinyl esters and polyurethane are the most commonly used resins ([Liang et al., 2015](#); [Zoveidavianpoor and Gharibi, 2015](#)). The purpose of coating is to enhance the strength of grains by improving the sphericity and roundness. It is also to reduce migration of fine crushed particles by entrapping them in the coating. According to [Economides \(2009\)](#), fine particles that are produced due to crushing of the proppant, as a result of high stress, can cause plugging of the pack pore. Hence reducing the formation conductivity. Moreover, the fines, which were produced during production or transportation, are also detrimental to the handling personnel. The coating can either be pre-cured (fully cured during manufacturing) or curable (cured in the formation fractures). The curable resin coated proppants are typically used in formations, whereby there is a tendency of proppant flowback during production operations. This is prevented by the formation of a consolidated pack as the curable coatings bonded each grain on their surface, resisting the flowback ([Economides, 2009](#)).

To allow industries to make the economic analysis that helps them with operational decisions, these basic types of proppant can generally be classified into three Conductivity Tiers as shown in [Fig. 1](#) ([Gallagher, 2011](#)). The hierarchy of the proppants are based on their conductivity, with ceramic being in Tier 1 and having the greatest conductivity. Followed by resin coated sand in Tier 2 and finally uncoated sand in Tier 3. Higher hierarchy rank in the pyramid indicates higher cost of proppant. In the current proppant market, sand proppant still dominates due to its abundance in nature ([Mordor Intelligence, 2020](#)). However, ceramic and resin-coated proppant is increasing in demand due to the needs of higher strength proppant for use in deeper wells.

2.2. Multifunctional proppant

With the progress of technology, coated proppant can also be made to have multifunctional properties. It can be used as traceable proppant, multiphase flow enhancer, for contaminant removal, as slow-release breaker, slow-release solid scale inhibitor, slow-release paraffin inhibitor and even to aid in proppant transportation ([Liang et al., 2015](#); [Zoveidavianpoor and Gharibi, 2015](#)). This can be done by incorporating the materials into the resin coating or impregnated into the porous media of the proppant and then encapsulated. The proppant transportation could be aided via modification of the surface of the coatings, such as in self-suspending proppant. Apart from the traceable and self-suspending proppant, the rest will be summarised into chemical infused proppant. A summary of the multifunctional proppant technology is given in [Table 1](#).

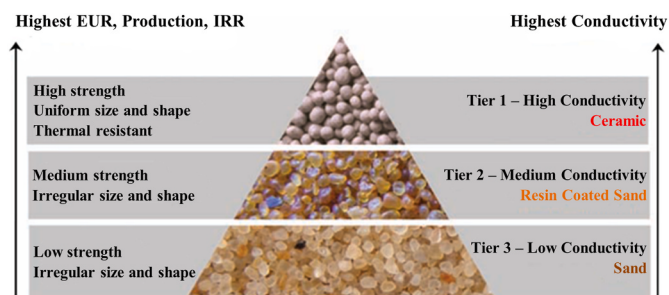


Fig. 1. The hierarchy of proppant based on conductivity ([Gallagher, 2011](#)).

Table 1
Summary of multifunctional proppant technology.

Proppant type	Application	Technology	Description	Reference
Traceable Proppant incorporated with tracing material either in the coatings or directly in the pores.	Allows tracing of the proppant propagation in formation.	Incorporation of radioactive material.	- Materials emit gamma rays that can be detected, recorded and analysed in real time or recorded for later analysis via gamma ray logging tool. - Disadvantage: issues in the handling, transportation, storage and environmental concerns due to short half-lives of the radioactive.	Liang et al. (2015)
		Incorporation of non-activated radiation-susceptible materials.	- The material is activated by using a pulsed or continuous neutron source and then the gamma ray detector attached to the logging system can detect the gamma rays emitted from the neutron activated tracers. - Disadvantage: Requires data processing correction due to fact that neutron source can also activate other nuclei presented in the formation.	McDaniel et al. (2012)
		Incorporation of HTNCC at low concentrations.	HTNCC absorbs neutrons and thus the tracing can be analysed through changes to neutron levels that can be detected via conventional compensated neutron logs or pulsed neutron capture tools.	Duenckel et al. (2011)
Chemical infused Incorporation of chemical into the porous cavity of proppant or encapsulated in the proppant coating or both.	Depends on the chemical incorporated such as: - multiphase flow enhancer, - contaminant removal, - slow-release breaker, - slow-release solid scale inhibitor, - slow-release paraffin inhibitor.	Incorporation of electromagnetic material. Introduction of solid scale inhibitor into the porous cavity of proppant.	- Proppant placement detected from the difference in EM. - Chemical diffusion works in three stage: - First stage: dissolution of the solid inhibitor when it comes into contact with water. - Second stage: dissolved inhibitor diffuses to the proppant's surface. - Third stage: the inhibitor diffuses from proppant's surface into the water. - Disadvantage: incorporation directly in proppant's cavity affects the structure integrity of the proppant and thus the conductivity.	Palisch et al. (2016) Webb et al. (1997)
Self-Suspending Coating the proppant with swellable polymer.	Enhancement of proppant transport and reduction of formation damage.	Cationic poly (diallyldimethylammonium chloride) coated sand.	- Swellable polymer forms hydrogel sphere upon contact with water. - Pumps and tubular abrasion were also reduced due to the hydrogel's friction-reduction properties.	Mahoney et al. (2016)

2.2.1. Traceable proppant

The success of HF operation is highly dependent on the zones of fracture, its geometry and how the proppant settle in these zones. There are several wireline diagnostic methods that can be utilised to study these. However, the use of wireline tools for HF evaluation is not favourable as it increases the operational costs and risks (Han et al., 2014). This is where traceable proppant comes into play. Usually, traceable proppants are made by incorporating radioactive material that emits gamma rays into the proppant. According to Liang et al. (2015), there are four ways the radioactive tracers can be made by:

1. Coating sand with radioactive materials,
2. Mixing with pulverised natural radioactive materials,
3. Impregnating radioactive ion exchange resins or
4. Grounding plastic into the proppants.

The gamma ray emitted by these materials can be detected, recorded, and analysed in real time or recorded for later analysis via gamma ray logging. This method has proven to be very effective in the HF process. However, the relatively short half-lives of the radioactive materials make the handling, transportation, storage and environmental concerns a serious issue to counter in its application.

To solve this issue, McDaniel et al. (2012) have patented a technique that utilises non-activated radiation-susceptible materials which can be activated by a neutron source. These materials are fused into the resin coating of the proppant or directly integrating them into the composite composition of the proppant (as shown in Fig. 2). The activation of the radiation can be performed in-situ by moving a logging tool, which contains a pulsed or continuous neutron source past the intervals

containing the traceable proppant. Then, the gamma ray detector attached to the logging system detect the gamma rays emitted from the neutron-activated tracers. Unfortunately, the neutron source can also activate other nuclei presented in the formation. Hence a corrective measure for the gamma rays from naturally occurring materials needs to

Non-activated

radiation-susceptible material

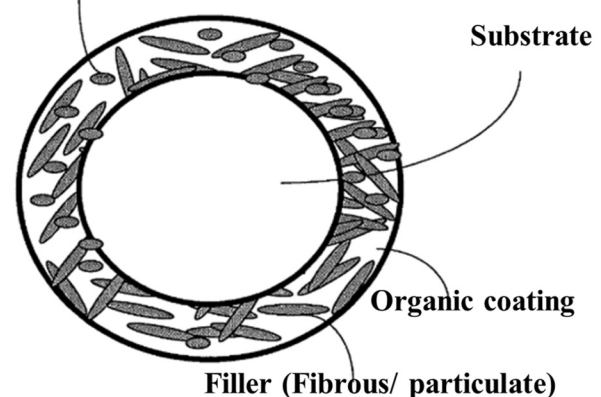


Fig. 2. Exemplary embodiment of a tracer incorporated proppant elements (McDaniel et al., 2012).

be considered when processing the data. This can be done by acquiring the background radiation during activation and subtracting it from the peak energy radiation data. In addition, the logging speed could also be slowed down by the long activation time of nuclei with long half-lives.

Another technique to address this problem is by incorporating a high thermal neutron capture compound (HTNCC) into each ceramic proppant grain. It can be incorporated during manufacturing at a sufficiently low concentration to avoid jeopardising the proppant properties. This novel technique can detect the fracture geometry without using radioactive elements, as was reported by [Duenckel et al. \(2011\)](#). Since HTNCC absorbs neutrons, the tracing can be analysed through the changes to neutron levels. This can be detected via conventional compensated neutron logs or pulsed neutron capture tools. The possibility of this method in effectively characterising the fractures are also proved by [Han et al. \(2014\)](#). The authors proved the effective detection of HTNCC tagged proppant placement within fractures and cement through the illustration with log examples.

The latest breakthrough in tracer proppant is electromagnetic (EM) proppant ([Palisch et al., 2016](#)). This method utilises the EM difference to detect proppant placement in the formation. The ceramic proppant was made to have sufficient EM difference to the fracture by incorporating an electrically conductive coating on the surface of the proppant. [Fig. 3](#) shows the prototype of the proppant made by CARBO Ceramics. As in HTNCC method, this eliminates the use of dangerous radioactive materials. However, while field tests have shown that the proppant could be detected, the current detection system may not be able to detect proppant at low concentrations. So further refinements are currently underway ([Palisch et al., 2018](#)).

2.2.2. Chemical infused

As the name implies, the chemicals are introduced into the porous cavity of the proppant or encapsulated in the proppant coating or both. When the chemicals are introduced into the porous cavity of the ceramic proppant, the releasing mechanisms work by utilising the chemical elution rate. Whereas, in the polymer encapsulation method, the release of the chemicals is governed by the lifetime of the encapsulating agent. As the encapsulating agent degenerates over time, the chemicals are slowly released to the environment. However, when both methods are used in tandem, the encapsulating agent mechanism is not governed by its lifetime. Instead, as the polymer of choice would be of a non-degradable quality, it will be via alteration of the chemical elusivity through its semi-permeable characteristics ([Saldungaray et al., 2015](#)).

One of the early works that introduced this method was by [Webb et al. \(1997\)](#). They introduced solid scale inhibitor into the porous cavity

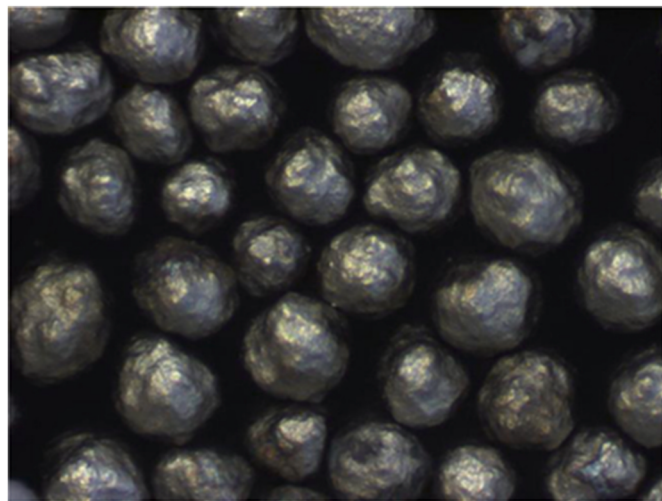


Fig. 3. 20/40 ceramic proppant with electrically conductive coating ([Palisch et al., 2016](#)).

of proppant. The slow release of the scale inhibitor can be summarised in three stages. First, when the solid inhibitor comes into contact with water, dissolution occurs. Then, the dissolved inhibitor diffuses to the proppant's surface. Finally, from the proppant's surface, the inhibitor diffuses into the water.

However, the introduction of the porous cavity into the proppant itself is undesirable. It affects the structural integrity of the proppant and thus, the conductivity. [Duenckel et al. \(2014\)](#) argued that this could be reduced by only introducing a fraction of porous proppant in the proppant mixture. The porous proppant has been designed with a minimal degree of porosity and a suitable starting raw material for this particular application (such as in [Fig. 4](#)). It was also interesting to note that recent research into the application of nanotechnology have also allowed the controlled release of the encapsulated chemical to be introduced directly into the fracturing fluid. One particular research on this was by [Bose et al. \(2016\)](#), who introduced encapsulated breaker in the fracturing fluid. This may be an alternative when there is a concern on the impact of encapsulating this material into proppant on the proppant's strength.

2.2.3. Self-suspending

Self-suspending proppant (SSP) was first created by [Mahoney et al. \(2013\)](#) to be used in slickwater fluids in an attempt to reduce damage in the formation. Due to the lower viscosity of slickwater fluid, the proppant tends to settle earlier before it reaches the area of interest. [Mahoney et al. \(2013\)](#) resolved this problem by coating the proppant with swellable polymer, which forms a hydrogel sphere upon contact with water. The extent of this hydrogel layer, which leads to the increase of particles' volume and the decrease of density can be seen in [Fig. 5](#). The friction-reduction properties of the resulting hydrogen spheres also reduce abrasion of pumps and tubulars. The SSP designed by [Mahoney et al. \(2016\)](#) was made of a cationic poly(diallyldimethylammonium chloride) coated sand. The settling test showed that the SSP settling time is twice to six times longer, depending on the concentration and thickness of the poly(diallyldimethylammonium chloride).

SSP has also been proven to be successful in a field trial ([Goldstein and VanZeeland, 2015](#)) in a Mississippian Lime liquids-rich play and an Escondido formation. As the results, the gas production was increased about 45% and 55%, respectively. This proves that the efficiency of SSP in proppant transporting as well as reducing the proppant pack and formation damage as reflected by the increase in gas production.

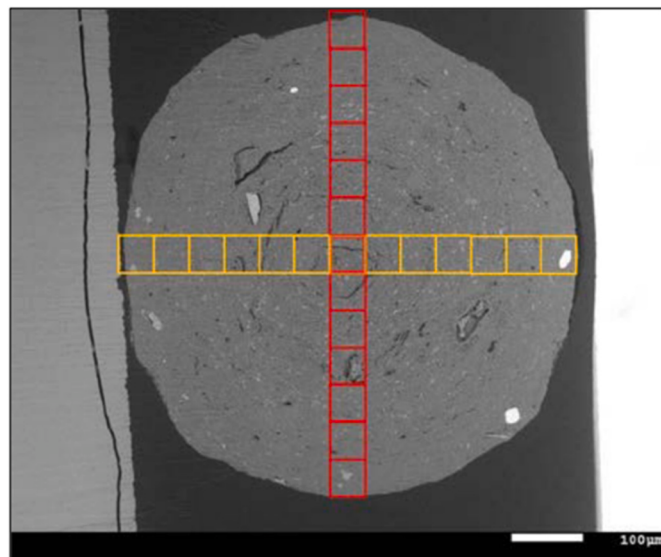


Fig. 4. SEM of cross-sectional image of porous proppant infused with chemical inhibitor ([Duenckel et al., 2014](#)).

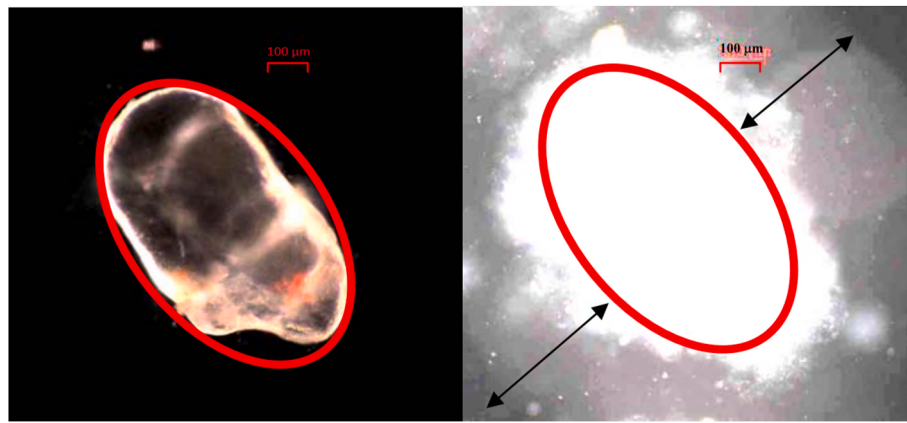


Fig. 5. Light microscopic images of hydrated 40/70 SSP grain at low and high brightness (Mahoney et al., 2013).

Table 2

Summary of ultra-lightweight (ULW) proppant.

	ULW Proppant	Reference
Description	Proppant that has both low specific gravity and the requisite mechanical properties to function as a fracturing proppant at reservoir temperature and stress condition.	Economides (2009)
Probable Materials	Walnut shells, pits, and husks.	Economides (2009)
Advantages	• Reduces immature proppant settling. • Requires low fluid viscosity to transport. • Allows for increased propped length.	Liang et al. (2015)
Example	Resin-impregnated and coated, chemically modified walnut hull. • Specific gravity: 1.25 (Subsequent development 2.02, 1.50 and 1.054) • Bulk density: 0.85 g/cm³. • Pressure tolerance: Up to 6000 psi (175 °F) with closure limit of 4000 psi (225 °F). Hollow metallic shell proppant made of lightweight metal: • Density: 0.6 g/cc to 2.5 g/cc. • Crush resistance: at least 3000 psi.	Wood et al. (2003) Smith et al. (2008)

2.3. Ultra-lightweight proppant

Ultra-lightweight proppant (ULW) was introduced in 2004. It has both low specific gravity and the requisite mechanical properties to function as a fracturing proppant at reservoir temperature and stress condition (Economides, 2009). According to Liang et al. (2015), there are three major trade-offs in using high density proppant; smaller fracture volume for a fixed weight of proppant, higher cost and faster settling rate in the carrier fluids. Fast settling rate is highly detrimental, as this leads to immature settling of the proppant. Usually this are rectified by using high viscous fracturing fluids. However, this is not feasible in the formation like shale reservoirs that requires the use of low viscosity fluid. Hence the need of ULW proppant, as its low density reduces immature proppant settling, while requiring low fluid viscosity to transport and allows for increased propped length (Liang et al., 2015).

Low specific gravity material, such as walnut shells, pits, and husks are usually the material of choice for ULW proppant. In fact, the first generation of ULW proppant comprises of a resin-impregnated and coated, chemically modified walnut hull, as reported by Wood et al. (2003). The proppant produced possessed a specific gravity of 1.25 and a bulk density of 0.85 g/cm³. At 175 °F, it can tolerate up to 6000 psi closure stress. However, as the temperature increases, the maximum closure stress limitation decreases, with the closure limit being 4000 psi at 225 °F. Subsequent development has yielded additional ULW proppant with specific gravities of 2.02, 1.50 and 1.054 as reported by Economides (2009).

Other than that, proppant fabricated with metal has also been reported. In one patent, Smith et al. (2008) used lightweight metal to create a hollow metallic shell proppant. It possesses a high crush strength of at least 3000 psi with a density ranging from 0.6 g/cc to 2.5 g/cc. The high crush resistance and ductility of metals or metals alloy, instead of collapsing, caused the proppant to partially deform under stress while still allowing oil and gas to pass through it. A summary of the ULW proppant can be seen in Table 2.

2.4. Self-generating proppant

While there have been several previous attempts, the idea of self-generating proppant by Chang et al. (2015), who investigated a revolutionary way for in-situ generation of proppant by transforming fracturing fluid into self-generating proppant, was a game-changing study towards high-strength, high-resistivity proppant. In this method, two precursor formulations in the form of liquid acts as both fracturing fluid and proppant as it solidifies into spherical beads in a static condition. The solid-free fracturing fluids eliminate erosional problems occurring. Additionally, the process's physical chemistry produces beads of good sphericity, which leads to a higher fracture conductivity due to highly uniform packing, and the sizes of the beads can be tuned using thermochemistry. Testing of the mechanical properties showed that it has a sufficient strength superior to intermediate strength proppant (ISP). The superiority of self-generating proppant is supported by findings by Zhang et al. (2019) who evaluated the physical properties and conductivity of self-generating proppant. The self-generating proppant studied shows good crush resistivity at pressure up to 55 MPa. In their research, the superior conductivity of such proppant was also proven, although the performance decreased rapidly with the increase in closure stress.

2.5. Unconventionally shaped proppant

Unconventional rod-shaped proppant was first introduced by McDaniel et al. (2010) (as shown in Fig. 6(a)). The rod shape idea came from many geologists' conclusions that cylindrical shaped particles provide a wider range of packing in comparison to particles of spherical shape. In addition, the elongated shape helps in reducing turbulent effect during proppant transport in the hydraulic system. Hence minimises frictional loss, as supported by Lin and Liang (2010). Over the last near decade since its introduction, many successful field applications have been reported (Abdelhamid et al., 2013; Gawad et al., 2013; McDaniel et al., 2010; Soetikno et al., 2014; Valiullin et al., 2015). The findings from these field applications are summarised in Table 3. However, while the application has been a success, the long term-effect of elongated shape on the conductivity is yet to be ascertained.

Apart from that, Liu et al. (2015) proposed another unconventional



Fig. 6. Unconventional shaped proppant (a) rod shaped proppant (McDaniel et al., 2010) (b) butterfly shaped proppant (Liu et al., 2015).

Table 3
Summary of unconventional rod-shaped proppant field test.

Reference	Location	Field type	Permeability (mD)	Depth (ft)	Findings
McDaniel et al. (2010)	Egypt	Moderate permeability oil reservoirs.	1–10	4000–7000	• Successful field trial with existing well-site delivery equipment without any adverse effects on fracturing or downhole equipment. • Well production increased.
Abdelhamid et al. (2013)	Silah field, El-Fayoum, Egypt	Medium sized, mature field.	~1	6284–6294	• Improved initial production evaluation. • Effective zero screen-out achieved.
(Edelman et al., 2013)	Arta fields, Egypt	Upper Nukhul formation of Arta fields consist of vertically stacked conglomerate, occasionally sandstone, and sandy limestone lithofacies.	0.003–12.8		• Enhanced pack stability of rod-shaped proppant pellets provides inherent flowback protection lead to zero flowback. • Cost reduction (~\$50 K per well) from rig time, cleanout job and pump replacement costs as well as deferred shut-in production.
Gawad et al. (2013)	Qarun field, Cairo, Egypt	Medium-size, mature oilfield consisting of sandstones and carbonates.	1–5	5000–6500	• 85% increase in production. • Zero screen-outs. • No proppant flowback.
Soetikno et al. (2014)	Sumatra Island, Indonesia	Mature waterflood field consisting shale and laminated sandstone.	<50	4200–4900	• 18%–30% increase in production. • No proppant flowback.
Valiullin et al. (2015)	Urevscoe and Potochnoe field, Western Siberian, Russia	Mature oil fields consisting of: • Jurassic formation. • Achimov formation.	0.3–0.5 0.4–0.7	~8264 - 8350 ~8563 - 8826	• 20% wells productivity enhancement. • No proppant flowback.

butterfly-shaped proppant. In their research, the proppant was designed with high drag in mind. It resulted in the proppant tumbling and fluttering during sedimentation in water, which greatly reduced the settling rate, as shown in Fig. 6(b). In a laboratory experiment, the sedimentary test showed 20–60% increment in settling time. In addition, they also claimed that the interlocking tendencies of the butterfly shaped proppant were also expected to reduce proppant flowback. However, no experimental evidence was provided. Moreover, no field testing has yet been reported, leaving the application of this type of proppant to still in the experimental stage.

The proppant technologies are still rapidly advancing. Some other proppant technologies apart from the discussed includes neutral wettability proppant, expandable proppant, and CO₂ carrier proppant for enhance recovery which can be read further in the recent critical review by Danso et al. (2021). These new emerging proppant technologies may pose challenges in standardising the evaluation of proppant due to its diverse characteristics.

2.6. Channel fracturing

Channel fracturing is one of the latest fracturing technologies in which proppant pack is placed in the fracture in discontinuous manner

as in Fig. 7. The discontinuous placement of proppant is achieved by injecting the proppant-laden fluid into the fracture in short pulses, alternating with pulses of proppant-free fluid. The idea of discontinuous proppant pack has been around since 1975 (Tinsley and Williams, 1975) but it has only start to be implemented in 2010 in Loma La Lata field, Argentina by Schlumberger (Gillard et al., 2010). The lack of implementation back then could be due to cost and technological limitations, particularly in the proppant pillar stability. With the application of fibre and agglomerating agent, higher proppant pillar stability could now be achieved by preventing proppant migration.

Following the first field application, several other successful field applications have been reported, showing increase in conductivity ranging from 32% to 68% (Altman et al., 2012; Gillard et al., 2010; Rhine et al., 2011). In addition, the requirement of fracturing fluid and proppant were also reported to be lower with little to no screen outs (Gillard et al., 2010; Rhine et al., 2011; Salah et al., 2017). This leads to a more cost-saving operation in comparison to the conventional fracturing technique. However, there is one major flaw to this technique. If the proppant was placed too dispersed it will lead to large column spacing causing the fracture to collapse (Hou et al., 2016; Khanna et al., 2014). Hence requiring further research on measuring the optimal volume fraction for the fracture network.

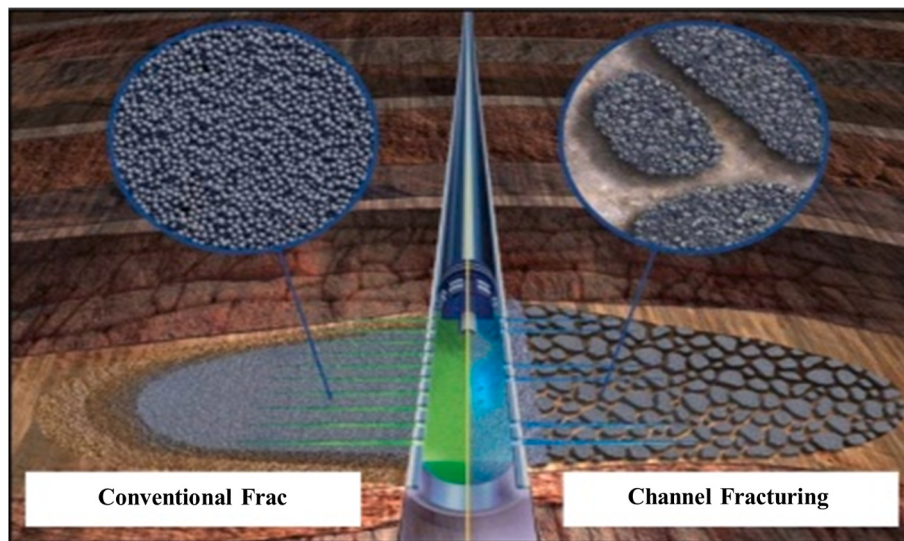


Fig. 7. Representation of channel fracturing (right) with respect to conventional fracturing (left) (Gillard et al., 2010).

3. Proppant characteristics and evaluation

The latest published API recommended practices in evaluating the characterisation of proppant is the [API RP 19C](#) (ISO 13503–2 identical). The API RP 19C provided the recommended practices in the evaluation of proppant used in HF and gravel-packing operations. It comprises of seven characteristics; the sieve analysis and median diameter determination; sphericity and roundness; acid solubility; turbidity; loose pack bulk, apparent and absolute density; crush resistance; and loss on ignition. [Fig. 8](#) summarises the importance of these characteristics in relation to the proppant performance. This section will discuss the challenges faced by the current testing technique in the advent of advancing proppant technologies and the improvements that have been proposed. However, out of the seven characteristics, turbidity, density, and loss on ignition testing will not be discussed, as the techniques established were already comprehensive and impeccable.

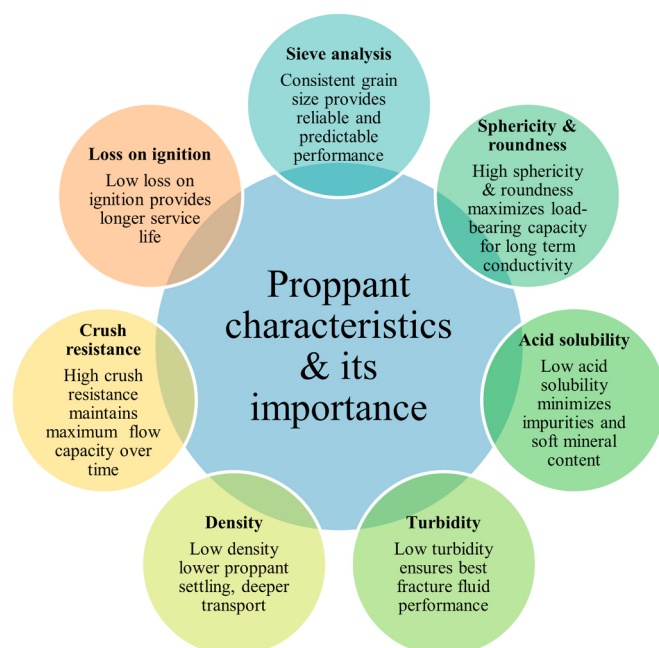


Fig. 8. Proppant characteristics and its importance.

3.1. Sieve analysis and median diameter determination

The sieve analysis and median diameter determination is performed to ensure consistent size of the proppant. The variability of sizes can cause plugging due to proppant rearrangement under stress. In accordance with the API RP 19C, at least 90% of the proppant tested must pass through the coarse designated sieve but be retained on or above the fine designated sieve. For example, in a designated 20/40 sieve distribution, 90% of the proppant must pass through the 20 sieve but be retained on or above the 40 sieve.

The current sieve analysis and median diameter are straightforward method and are easy to implement in the industry. While there is a broad distribution of the mean diameter, there is no drop in porosity. Hence posed no significant effect on conductivity. This has been proven by Berg's equation (Equation (1)), which shows that permeability is dependent more on porosity while permeability is directly related to conductivity (Schubarth and Milton-Taylor, 2004).

$$k = 5.1 \times 10^{-6} \phi^5 d_{50}^2 e^{-1.385(d_{90}-d_{50})} \quad (1)$$

Apart from the sieve method, a new way to measure particle size distributions is laser diffraction technique. This method has yet to be adopted in the API standards. While the two methods measure a different aspect of particles, according to Kumar et al. (2013), for particles up to around 500 μm , the particle size reading is comparable between the two techniques. However, for particles with a d_{90} above 500 μm , sieve analysis is preferred when feasible.

Nevertheless, the emergence of newly shaped proppant may have been proven to be a challenge to these two methods. In rod-shaped proppant, for example, varying length could definitely affect the conductivity, as researchers have found that the greater the length of the proppant, the more susceptible it is to being crushed (Jia et al., 2019). While the median diameter can be easily determined via optical microscope and software (McDaniel et al., 2010), there is still a question about the consistency of the proppant length. Sieving method is only based on the maximum length and maximum width. In the case of excessive elongation, the length of the proppant may affect the passage of particles through the sieve aperture (Allen, 2003). This is supported by Bartley et al. (2019) who found that the higher the aspect ratio (ratio of length to width, L:W) of the particle, the lower the precision of the sieve analysis, especially for a particle with an aspect ratio of 3:1 and higher.

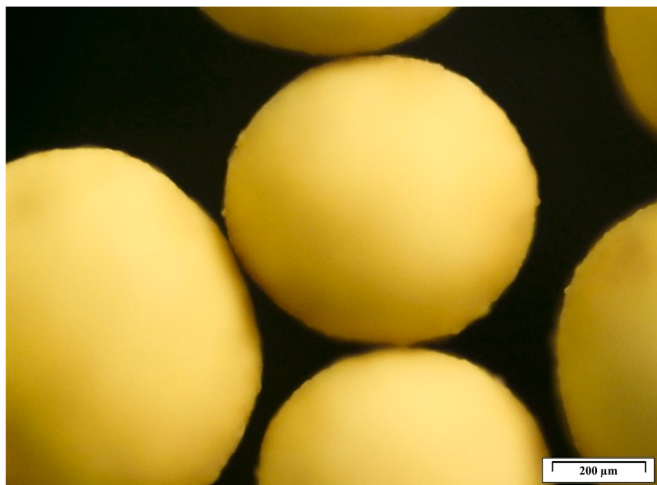


Fig. 9. An actual image of 20/40 ceramic proppant taken under optic microscope.

3.2. Sphericity and roundness

The sphericity and roundness of the proppant significantly affect the proppant crush resistance and conductivity. The higher the sphericity and roundness, the better the proppant crush resistance and conductivity. This is attributed to the wider distribution area of stress (Economides, 2009; Kamat et al., 2011; Zoveidavianpoor and Gharibi, 2016). Higher conductivity could also be achieved due to better proppant packing when the shape is round and even (Bose et al., 2015; Economides, 2009; Shekhawat and Pathak, 2016). This is especially true since conductivity is the product of permeability and pack width, which is affected by the shape and size of the proppant (Barree et al., 2003; Richard et al., 2019; War, 1989). Typically, the sphericity and roundness of the proppant are determined by taking a microscopic picture of the proppant (as shown in Fig. 9) and comparing it with the Krumbein and Sloss chart (Fig. 10). To eliminate data skewing, every particle in the field of view of the microscope should be evaluated. It is imperative to ensure that none of the proppant grains not touch each other. However, this is fully dependent on the operator that conduct the testing and is thus susceptible to human error.

With the advance on technology, human error could be reduced by

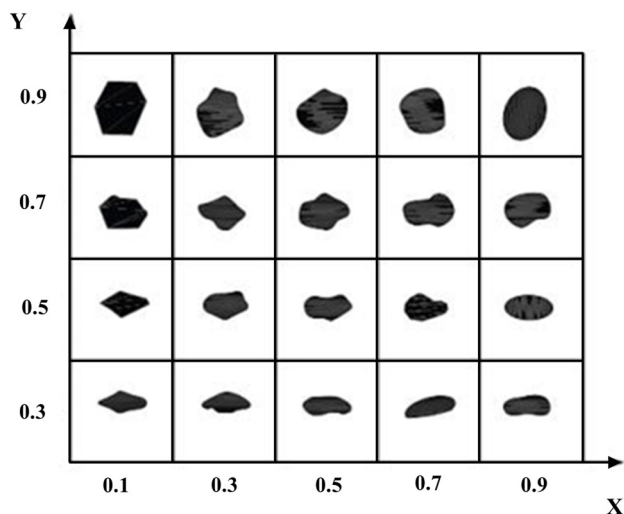


Fig. 10. Krumbein and Sloss chart (RP19C, 2018).

utilising software packages and digital equipment that can more accurately determine the sphericity and roundness of the proppant (Duenckel et al., 2016). Digital equipment, such as a dry dynamic particle analyser and laser diffraction equipment, has been widely used to analyse the size, sphericity and roundness of proppant (Kumar et al., 2013; Stauffer, 2014). Table 4 summarises the advantages of using digital equipment over the sieve and manual Krumbein-Sloss microscopic analysis for measuring the size and shape factors required by the API standard for proppant. In addition to reducing human error, these equipment are also more time efficient.

However, while it has been accepted that the better the sphericity and roundness of proppant, the better is its conductivity, this is only applicable for traditionally shaped proppant. With the emergence of unconventionally shaped proppant, there is need to revise the standards for the proppant shape and how it affects the performance of the proppant. When McDaniel et al. (2010) first proposed the rod-shaped proppant, a modified Krumbein Sloss chart has been introduced as a method to evaluate the shape of the new proppant (Fig. 11). In this modified chart, the proppant is evaluated in terms of rod straightness and roundness.

In addition to that, recently, Jia et al. (2019) proposed a mathematical modelling to calculate the effect of the shape on the proppant conductivity. This mathematical modelling was an attempt to describe permeability in terms of porosity. They started with defining the packing porosity, proposing a simplified loose packing empirical model (Equation (2)) to find the corrective factor, C_0 , for the conductivity equation proposed (Equation (3)). The packing porosity was based on the least square method, which allows the calculation of the porosity of the fracture with rod-shaped proppants to be in loose and close packing patterns. The new modelling has shown a good fit compared to the model proposed by Zou and Yu (1996). Using this empirical model, the studies showed that the embedment of close packing of cylindrical proppants (having sectional diameter and length of 1 mm) is considerably lower. This leads to higher conductivity compared to spherical proppant (diameter of 1 mm). However, further evidence is required in the accuracy of the proposed method in determining the quality of rod-shaped proppant, especially since there has been a lack in the study on what is the best aspect ratio that maximises the proppant's strength and conductivity.

$$\Phi_0 = 1 - \frac{9.87}{\lambda + 1/\lambda + 13.325} \quad (2)$$

$$kW_f = C_0 k_f (X - 2\alpha') \quad (3)$$

3.3. Acid solubility

The acid solubility test is important to test the chemical resistivity of the proppant. The operating condition in the reservoir may be acidic, especially when mud acids consisting of hydrochloric acid (HCl) and hydrofluoric acid (HF) were used for the removal of near-wellbore damage (Assem & Nasr-El-Din, 2017; Assem et al., 2017; Cheung, 1988; Fuss et al., 2008). These acids could corrode or even leach the compounds in the proppant, jeopardising the structural integrity of the proppant and thus, reducing its strength. In API RP 19C, the acid solubility test was performed by immersing the proppant in a mixture of HCl and HF at a ratio of 12 to 3. The maximum acid solubility should comply with the API standards as shown in Table 5.

However, interestingly, Fuss-dezelic (2015) found that the components that are leached out from the proppant are more pronounce at dictating the acid resistivity over the amount of compound that is being leached out. This is especially true for ceramic proppant as shown in her work. The mechanical properties of ceramic proppant, while conforming to the acid solubility requirement of lower than 7%, is not proportional to the value of acid solubility measured (Fuss-dezelic, 2015). In a prior study by Fuss et al. (2008), the crush resistance of bauxite based

Table 4

Digital equipment advantages over sieve and manual Krumbein-Sloss microscopic analysis for measuring the size and shape factors required by the API standard for proppant (Stauffer, 2014).

Description	Digital Equipment	Sieve Analysis	Manual Krumbein-Sloss microscopic analysis
Ease and accuracy of measurement	Multiple size and shape parameters reported in one automated measurement of up to hundreds of thousands of measurements each individual particle, taking only a few minutes to complete.	Fifteen-minute manual ensemble sieve analysis subject to operator error and worn sieves giving one size, equivalent spherical diameter.	Up to a day-long subjective manual microscopic analysis to get representative sample, giving two estimated mean shapes.
Data reported	Report on multiple size, shape and parameter. Possible report form: - graphical and tabular number or volume distributions, with means and much more summary data. - two- parameter comparative scatter diagram isolating the relationship between any two parameters. - stored re-measurable sortable viewable printable image file of each particle.	- One size analysis as a mass distribution with mean values and a few other summary data. - No data is given for each individual particle, only for the entire ensemble sample.	A subjective operator-dependent estimate of two shape factors, as mean values of the entire population measured.
Dimensionality	- All three major axes of each particle are measured and reported providing a far more accurate volume size distribution than equivalent spherical diameter calculated as an ensemble volume distribution. - Shape parameters are ratios of various size parameters, which give the most accurate and automatic shape data quickly and easily measured.	Sieve analysis gives only an equivalent spherical diameter size parameter.	Manual microscopic analysis gives only operator-estimated means of a 2-D analysis for two shapes.

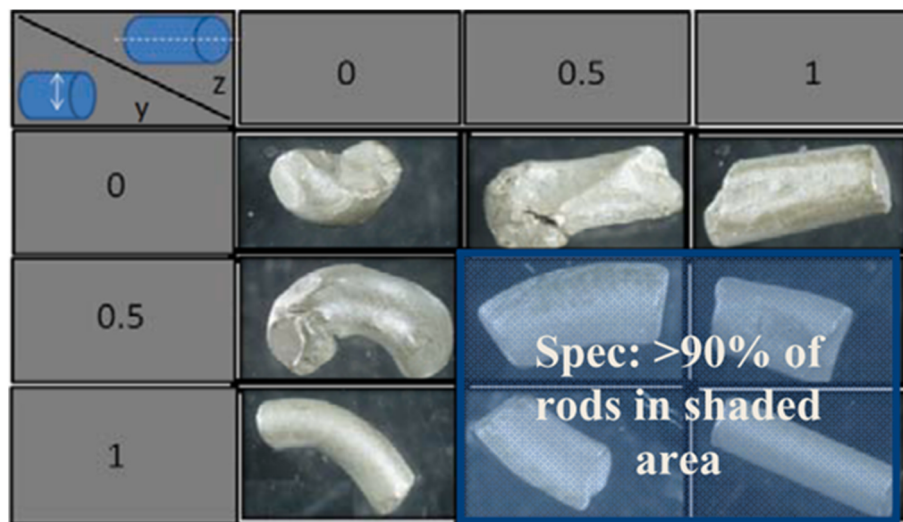


Fig. 11. Modified Krumbein chart for evaluating of rod shape: z – rod straightness; y – roundness and smoothness along rod length (McDaniel et al., 2010).

intermediate-density ceramic proppant (IDP) and a kaolin clay based lightweight ceramic proppant (LWP) was tested after they were exposed to a 60-min acid solubility test. Fig. 12 shows the crush resistance results as a function of time in acid exposure at a pressure of 8000 and 10,000 psi. The resulting rate of acid solubility of IDP and LWP were recorded as 7.8×10^{-2} wt%/min and 6.1×10^{-2} wt%/min, respectively. Based on this, IDP would have failed the acid solubility test. However, the crush resistance data for IDP after acid exposure proven otherwise. Despite the higher rate of acid solubility in IDP, its crush resistance remains constant. In fact, contrary to popular belief, at higher pressure, the crush

resistance slightly improves with time.

Fuss et al. (2008) attributed this to the microstructure of the proppant. In the IDP, the mullite-corundum structural matrix was not affected by the inter-crystalline, silica-rich, matter etched by the acid, as shown in Fig. 13. Meanwhile, in LWP, the ‘skeleton’ structure exhibits a small needle-like crystallite structure with surface pits post-acid treatment, as shown in Fig. 14. This kind of structure leads to high stress in the proppant and reduces its crush resistance. “This is also consistent with the finding by Wu et al., 2019 and Gestel et al. (2003) that structure with high crystallinity have a stronger corrosion resistance.”

Fuss-dezelic (2015) findings exposed the weakness of API RP 19C in evaluating unconventional proppant. Nevertheless, it should be noted that API RP 19C is only interested in estimating the effectiveness of mineral separation techniques in eliminating the softer and less

Table 5

Proppant maximum acid solubility ((RP19C, 2018).

Proppant Type and Size	Maximum Acid Solubility % by weight
HF sand, resin-coated proppant, and gravel-packing sand proppants	
Larger or equal to 30/50	2.0
Smaller than 30/50	3.0
Ceramic proppants and resin-coated ceramic proppants	7.0

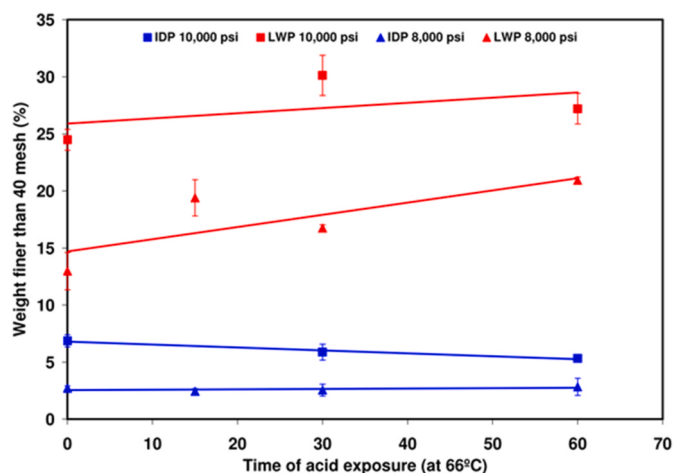


Fig. 12. Crush Resistance results of IDP and LWP specimens as a function of time of acid exposure at a pressure of 8000 and 10,000 psi (Fuss et al., 2008).

desirable cementitious minerals from quartz sand. The amorphous glass phases as well as other compounds, such as magnetite, alkalis and iron oxides, that are usually present in the case of manmade ceramic proppant are also soluble in HCl/HF mixtures.

3.4. Crush resistance

Fine particles that are produced due to crushing of the proppant as a

result of high stress can cause plugging of the pack pore, reducing the formation conductivity (Economides, 2009; Fu et al., 2016; Mittal et al., 2018; Zoveidavianpoor and Gharibi, 2015). The crush resistance testing in API RP 19C is a static pressure test. It is measured by applying stress in increment until the proppant crushing reaches 10% or more. While the API RP 19C crush resistance procedure provides a way for the industries to measure the strength of proppant, it does not realistically account for the condition in the field. It neglects the negative effects of pressure on proppant and fracture conductivity (Simo et al., 2013). While API RP 19C did warn that it does not simulate the actual condition of the field, it is still far from the ideal ways to evaluate crush resistance of the proppant. Palisch et al. (2009), concurred by stating that it overlooked the geometry and structure of the proppant and the fracture. It also oversimplified and overgeneralised the analysis and is susceptible to human errors.

Another point to be concerned about is the reliability of the crushing test in coated proppant. As highlighted by Economides (2009), one of the functions of coatings is to entrap fines generated from proppant crushing, preventing fines migration. However, the entrapment of fines within the coating prevents an accurate lab measurement of crush resistance, which is reliant on the recovered generated fines. In addition, although fines were entrapped, the crushing of the proppant substrate alters the shape, as shown in Fig. 15, leading to changes in the proppant pack and consequently, proppant conductivity.

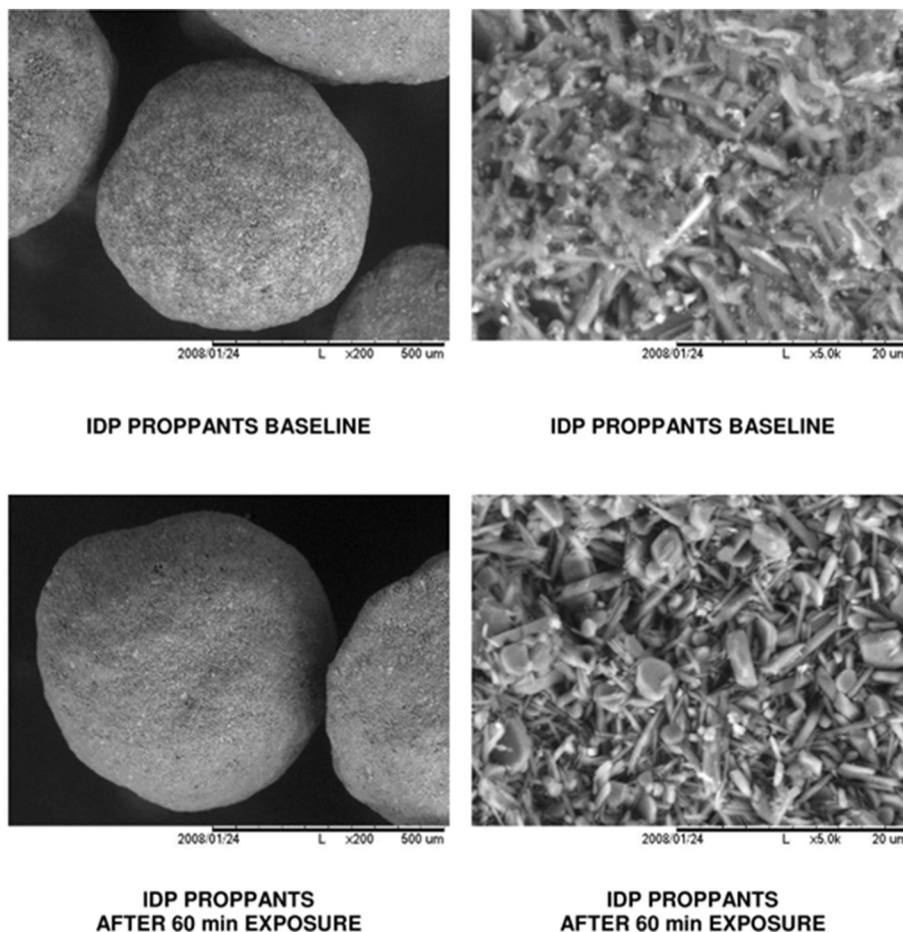


Fig. 13. Scanning electron micrographs of IDP proppant surface before and after exposure to acid (Fuss et al., 2008).

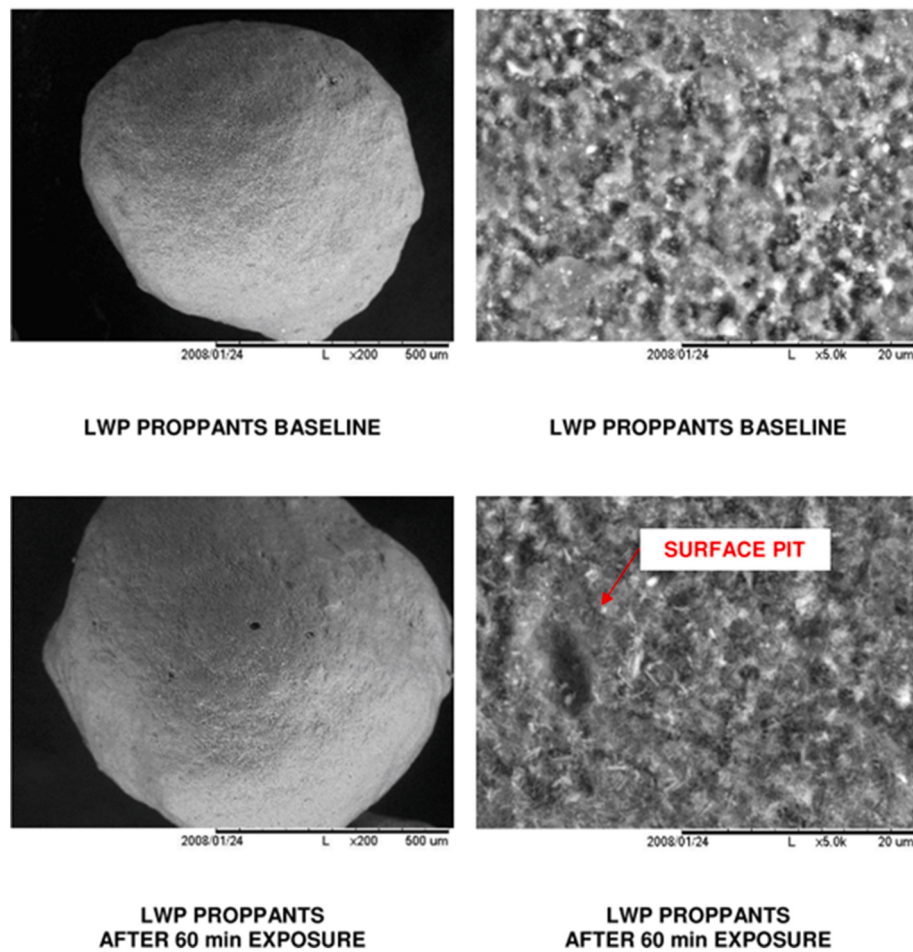


Fig. 14. Scanning electron micrographs of LWP proppant surface before and after exposure to acid (Fuss et al., 2008).

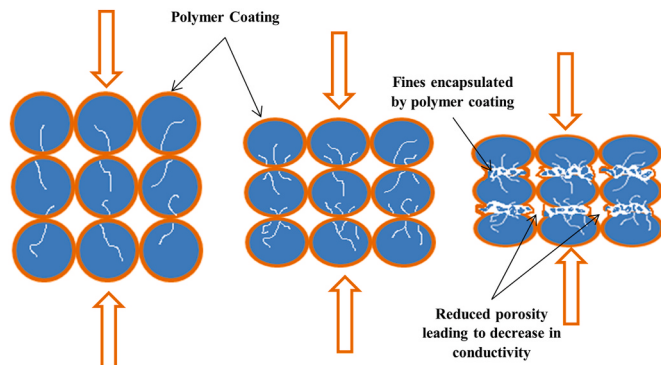


Fig. 15. Response of coated proppant upon crushing.

4. Proppant conductivity

4.1. Background

Following the emergence of HF, the interest in the evaluation of proppant conductivity has increased. Prior to the mid-1980s, many different linear and radial flow testing cells were used to measure proppant conductivity (Gidley et al., 1989; Schulz, 2014). After 8 years of development, the API finally establishes API Recommended Practice 61 (API RP 61) for measuring proppant conductivity based on the testing guidelines by Penny (1987). The practice comprises a single-phase liquid flow through a $7 \times 1\frac{1}{2}$ in. Linear proppant pack cell (Fig. 16) at

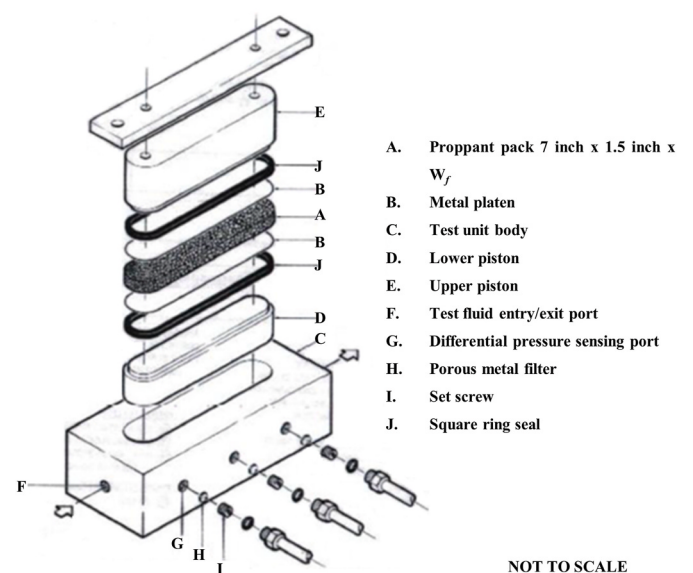


Fig. 16. Exploded schematic diagram of API proppant packed conductivity test unit (RP19D, 2008).

flow rates of 1–10 mL/min (API RP 61). The calculation of the permeability at a given stress condition followed Darcy's law, utilising the pressure drop measurement across ports that were located adjacent to the proppant.

Due to the lack of proppant settlement (Brown and Economides, 1992; McDaniel, 1986), the API RP 61 was deemed as short-term conductivity test. Generally, the testing procedure requires the cell to be loaded with 2 lbs/ft³ of proppant and then the load is increased in 2000-psi increments, with 15 min holding at each stress level. During this process, the fluid test, which in this case was distilled water, was flowed at rates from 2.5, 5 and 10 mL/min.

ISO 13503-5 was published in 2006, replacing API RP 61 for long-term conductivity testing. The new procedure retains the apparatus of API RP 61, but many of the parameters have been revised to cover long-term testing. One of these is the period under stress. It has been changed to 50 h, as findings shows that proppant reached semi-steady state around this period (Brown et al., 1992; Kaufman et al., 2007; API RP 19D). Economides (2009) supports this finding, stating that the 15-min steps in the short-term API test procedures are insufficient in allowing the proppant pack to stabilised under the new loading conditions. In addition to the testing time, the new standard (ISO 13503-5) also features the addition of temperature constraint, deoxygenation of the cell, replacement of the steel platens with Ohio sandstone and the introduction of silica-saturated liquids as the test fluid to replicate the conditions in the reservoir. These also reduce the interaction induced by the test procedure between the fluids and the test apparatus, sandstone platens and proppant.

It has been recognised by many researchers, including Cooke (1973) that temperature affects the performance of proppant packs, especially since it affects the viscosity of the test fluid, which is fundamental to the conductivity equation (Duenckel et al., 2016; Penny, 1987). Hence ISO 13503-5 states that the minimum temperature in the test cell and proppant pack should be 121 °C (250 °F) for ceramic and resin-coated proppant. For naturally occurring sands, it should be at 66 °C (150 °F). As for silica saturation vessel, the temperature must be above the test cell and proppant pack temperature by 20 °C (35 °F) and 11 °C (20 °F) respectively. The reason for the higher temperature constraints for ceramics and resin-coated proppant was due to its application at deeper formation, which usually entails higher pressure and temperature environment.

The replacement of steel platens with Ohio sandstone is to provide a modest illustration of embedment, which is lacking in API RP 61. Penny (1987) conducted an evaluation on the effect of the platens used in the test and found that the conductivity of steel platens are higher than the Ohio sandstone platens, as shown in Fig. 17. The reasoning was due to the lack of embedment in steel platens. Another factor that contributes

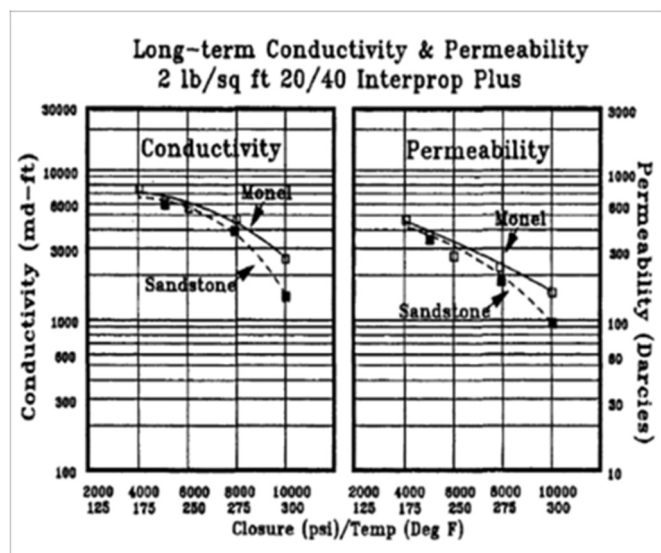


Fig. 17. Comparison of conductivity and permeability of steel vs sandstone (Penny, 1987).

Table 6

Specification comparison between API RP 62 and ISO 13503-5/API RP 19D.

PARAMETERS	API RP 61 (1989)	ISO 13503-5/API RP 19D
Cooke Cell	316 Stainless Steel Cooke Cell	
Flow Design	Linear	
Size of proppant pack cell	~7 × 1½ in.	
Permeability model	Darcy's Law	
Pressure increment	2000 psi	
Conductivity Term	Short	Long
Holding time for each pressure increment	15 min	50 h ± 2 h
Test Fluid	Dionised or distilled water	2% KCl in dionised or distilled water
Liquid flow	1–10 mL	2–4 mL
Core sample	Steel Platens	Ohio Sandstone
Removal of oxygen	No	Yes
Temperature	Ambient	Test Cell and Proppant pack: • 121 °C (250 °F) for Ceramics & Resin-Coated • 66 °C (150 °F) for naturally occurring sands Silica saturation vessel must be above the test cell and proppant pack temperature by: • 20 °C (35 °F) for Ceramics & Resin Coated • 11 °C (20 °F) for naturally occurring sands
Reference(s)	RP61 (1989)	RP19D (2008) and Kaufman et al. (2007)

to this trend is the 'wall effect' in which the width is modestly reduced and the effect of the high porosity/high permeability area of the proppant pack/steel core interface was eliminated as agreed by Duenckel et al. (2016).

Table 6 shows the specifications of the conductivity procedures, summarising the similarity and changes made to API RP 61 in ISO 13503, which was later in 2008, adopted by the API into API RP 19D. The standard was reaffirmed in 2015 and is currently under revision/update as stated by Duenckel et al. (2016). This is in line with the API instruction, in which the API Recommended Practice is to be reviewed and revised, reaffirmed or withdrawn at least every 5 years (Raysoni and Weaver, 2012). Although the procedure had been revised from API RP 61 to ISO 13503-5 and API RP 19D, one thing remains the same since 1987, which is the conductivity test unit despite the changes in the parameters.

4.2. Limitations and challenges in proppant conductivity analysis

The current standard procedure for proppant characteristics evaluation still has a long way to go, as there are still many theories behind its mechanism that is not fully understood. The current procedure is limited to certain parameters. Although there have been some attempts to change the conductivity test unit design over the years, not many works have reported on this in detail. Again, this could be attributed to the trend where researchers are currently focussing on mathematical modelling and simulations to predict the proppant performance. Table 7 shows a summary of the mathematical modelling of proppant conductivity from 2015 onwards. The Kozeny-Carman correlation is the most used mathematical modelling basis, such as in Xu et al. (2019), Tandon et al. (2018) and Guo et al. (2017), taking proppant embedment into consideration in the modelling. Equation (4) shows the original equation proposed by Kozeny (1927) and Carman (1938), which relates permeability with porosity, tortuosity, and grain size (Carrier, 2003; Lala, 2018; Ozgumus et al., 2014; Salem, 2001). The equation can be simplified based on the assumptions on these three parameters, resulting in the modified form seen in some of the equations in Table 7.

Table 7
Mathematical modelling of Proppant Conductivity.

Modelling basis	Assumptions	Equation(s)		Key Parameter(s)	Proppant size	Remarks	References
Analysis of experimental data	1. Ideal condition. 2. Multilayer packing acts similar to single-layer packing.	$F_{RCD} = \frac{74.8f_1(f_1 - 0.74)\left(Df_1 - D_1f_2 - \frac{2D_2\rho}{E_2}\right)}{0.5f_1^2 + 1}D_1^2$	(5)	● Embedment	10/20, 20/40	F_{RCD} increases with the increase in Df_1 , E_1 , E_2 and decreases with the increase in P .	Li et al. (2015)
		$f_1 = 1 - 2.08\left(\rho\frac{1 - \nu_1^2}{E_1}\right)^{2/3}$	(6)				
		$f_2 = 2.08\left(P\frac{1 - \nu_1^2}{E_1} + P\frac{1 - \nu_2^2}{E_2}\right)^{2/3} - 2.08\left(P\frac{1 - \nu_1^2}{E_1}\right)^{2/3}$ (Please refer to Equations (26) and (27) below table)	(7)				
Kozeny-Carman	1. Spherical and uniform size proppant. 2. Rhombohedral packing.			● Spherical proppant ● Number of packing layer	30/50 mesh proppant	This model is suitable for high pressure situations, when the formation thickness is approximately 3000 m.	(Li et al., 2016)
Modified Darcy Law	1. Isothermal condition. 2. A linear, steady state and compressible fluid flow.	$F_{RCD} = k.h = \left[\frac{2\mu z P_{SC} TL}{T_{SC} w_s (P_i^2 - P_{SC}^2)}\right] Q_{SC}$	(8)	● Nitrogen gas as fracturing fluid	20/40	F_{RCD} decreases with increase in P .	Shekhawat and Pathak (2016)
Kozeny-Carman	1. Uniform proppant distribution.	$F_{RCD} = k_{eq}^{1.2.3} \times w_f$ $k_{eq}^{1.2.3} = k_{eq}^{1.2} R_{s1} + k_3(1 - R_{s1})$ $\frac{1}{k_{eq}^{1.2}} = \frac{1}{k_1}(1 - R_{s2}) + \frac{1}{k_2}R_{s2}$	(9) (10) (11)	● Spherical proppant		F_{RCD} first increases to a certain vau before decreasing with increase in R_s .	Guo et al. (2017)
Analysis of experimental data	1. Uniform proppant distribution. 2. Viscoelastic proppant and formation rock.	$F_{RCD} = c_0 k_f w'(t) = \frac{\varnothing_c(t)^3 c_0}{120} \times 10^6 = \frac{\varnothing_c'(w - 2\alpha(t))^3 c_0}{12} \times 10^5$	(12)	● Heterogenous proppant placement	20/40	F_{RCD} decreases with decrease in α which is result of proppant embedment.	(Hou et al., 2017)
Lattice Boltzmann	1. Physical space under consideration is filled with a regular lattice occupied by discrete fictitious particles.	$V = \frac{K}{\mu} \nabla p$	(13)	● Rod-shaped proppant		Conductivity tests in the lab indicate the empirical relation valid for spatially periodical random close packings of spherical and elongated particles.	Osiptsov (2017)
Lattice Boltzmann Model (LBM)	1. Ideal condition. 2. Uniform closure stress. 3. Fully spherical proppant. 4. Fully filled fracture.	$F_{RCD} = w.k_{fp}$ $w = (1 - \varepsilon)w_i$	(14) (15)	● Spherical proppant	20/40	F_{RCD} decreases with decrease in w and k_{fp} due to reduction in compactment. A good agreement in comparison to Kozeny-Carman correlation over the full range of porosities was observed.	(Shamsi et al., 2017)
Kozeny-Carman		$k_{KC} = C_1 \frac{D_m^2 \varnothing^3}{(1 - \varnothing)^2}$	(16)	● Spherical proppant	50 mesh proppant	Change in pore structure can be potentially correlated to changes in the proppant pack permeability.	Tandon et al. (2018)
Schlumberger Doll Research	1. Fines has spherical shape. 2. Unmixed proppant mixture.	$k_{SDR} = C_2 \varnothing^m T_{2GM}^n$	(17)	● Spherical and crushed proppants	20, 30 mesh proppant		
Combination of Kozeny-Carman and Hazen	1. Proppant pack height is proportional to the proppant concentration.	$F_{RCD} = k.w_f$	(18)	● Proppant size and crushing	Ceramic proppant: 20/40 and 30/50, sand proppant: 20/40	A good agreement between the empirically estimated permeability and fracture conductivity and published conductivity test results was observed suggesting that grain size data should	(Zheng et al., 2018)
		$k = C \frac{e^3}{1 + e} \times D_{10}^2$	(19)				

(continued on next page)

Table 7 (continued)

Modelling basis	Assumptions	Equation(s)	Key Parameter(s)	Proppant size	Remarks	References
Kozeny-Carman	1. Horizontal fractures. 2. Rhombohedral packing. 3. Known fracture aperture. 4. Uniform proppant distribution. 5. Ideal condition. 6. Negligible rod-shaped particles' gravity.	$F_{RCD} = c_0 k_f (X - 2\alpha'')$ $k_f = 11.067 \frac{\left\{ X \left(1 - \frac{8.97}{\frac{d_r}{l_r} + \frac{l_r}{d_r} + 13.325} \right) - 2\beta'' \right\} (X - 2\beta'')^2 d_r^{\frac{4}{3}} l_r^{\frac{2}{3}}}{X^2 (X - 2\beta'') \left\{ 0.5 \left(\frac{X - 2\beta''}{X} \right)^2 + 1 \right\}}$	(20) (21)	• Rod-shaped proppant	be collected as supplemental data for permeability and fracture conductivity estimation. F_{RCD} increases with increase in d_r . For rod shaped proppant, these models match the fracture conductivity and permeability satisfactorily at different closure pressures.	Jia et al. (2019)
Kozeny-Carman	1. No initial stress and strain. 2. Proppant and rock matrix are elastomer. 3. Negligible proppant crushings. 4. Isothermal condition.	$K_f = \frac{\phi r^2}{8\tau^2}$ $F_{RCD} = K_f (W - u_m)$	(22) (23)	• Spherical proppant, rhombohedral packing	Increase in r , increases embedment, leading to more nonlinear decrease in change of F_{RCD} under the closure pressure. There is error in simulation which may be resulted by the ordered packing of spherical proppants and the neglect of proppant breakage and fines movement.	Xu et al. (2019)
Discrete Element Method (DEM)	1. Ideal proppant pillar. 2. Proppant laden fluid is incompressible.	$F_{RCD} = k_0 w_f$ $k_0 = \int_0^r \frac{2k_p k_f}{k_p l + 2(k_f - k_p)X} dy + \int_r^{1/2} \frac{2k_f}{l} dy$ $= \int_0^r \frac{2k_p k_f x}{[k_p l + 2(k_f - k_p)X](r^2 - x^2)^{0.5}} dx + k_f (1 - 2r/l)$ $k = \frac{\phi r_x^2}{8\tau^2}$ $F_{RCD} = 0.07(1 - \eta)(0.155R - 1.21RP_C^{2/3}T_1^{2/3})^2 \left\{ \frac{w_{f0}}{1.17\sqrt{\frac{E_{Y1}}{E_{Y2}}}} - 3.78RP_C^{2/3}[(n_2 - 1)T_1^{2/3} + T_2^{2/3}] \right\} \times \left\{ 1 - \frac{4/3N\pi R^3 - \pi R^3 P_C^{4/3}[6.5(N - n_1)T_1^{4/3} + 7.15n_1 T_2^{4/3}] + \pi R^3 P_C^2[2.25(N - n_1)T_1^2 + 4.5n_1 T_2^2]}{\left\{ \frac{w_{f0}}{1.17\sqrt{\frac{E_{Y1}}{E_{Y2}}}} - 3.78RP_C^{2/3}[(n_2 - 1)T_1^{2/3} + T_2^{2/3}] \right\} \times 10^2} \right\}$	(24) (25) (26) (27)	• Proppant size combination	While compression initially reduces proppant pillar porosity which reduces k_0 , breakdown of proppant pillar resulted in particle movement which increases the porosity again. However, despite this F_{RCD} generally decreases.	(Zhu et al., 2019)

Table 8
CFD coupling system.

Researcher	Coupled system	Application	Approach	Model type
Santos et al. (2018)	DEM	Simulation of SMP EP performance with different properties.	Modelling of motion of the particles by solving Newton's equations.	Soft sphere contact model.
Shi et al. (2016)	Extended FEM (XFEM)	Approximation of the displacement field.	By considering the displacement jump across fracture surfaces and the singular displacement field around the fracture tip..	Newton-Raphson iteration.
Wang et al. (2019)	DEM	Simulation of proppant transport and deposition in fracture and fracture network.	Fluid flow and particle movement were computed by the CFD and DEM solvers separately.	Soft sphere overlap model.
Xu et al. (2019)	FEM	Simulation of formation of proppants and formation.	By solving the equations governing the combination effect of different parts of proppant on the fracture pore.	Combination of mathematical modelling and Kozeny-Carman correlation.

$$k = (\gamma / \mu)(1 / C_{K-C})(1 / S_0^2) [e^3 / (1 + e)] \quad (4)$$

In addition, Lattice Boltzmann Model is also getting attention due to its efficiency in modelling fluid flow in porous materials (Osipov, 2017; Sanematsu et al., 2015; Shamsi et al., 2017). The main findings include the higher porosity of cylindrical proppant in comparison to conventional spherical proppant and the high independency of permeability on the loading at lower stresses (below 12 kpsi or 83 MPa). Furthermore, particularly in CFD, discrete and finite elemental methods (FEM and DEM, respectively) are also favourable as they are very effective in quasi-static modelling and the dynamics of granular materials deformation, as shown in Table 8 (Santos et al., 2018; Shi et al., 2016; Wang et al., 2019; Xu et al., 2019).

The trend is attributed to the fact that these methods provide faster and more accurate results. They can be designed to encompass more crucial factors, such as the multiphase effect, inertial effects of flow, proppant diagenesis, gel damage and many more that occur in the formation. Whereas laboratory experiments are usually limited to certain factors. This is confirmed by Economides (2009), who states that the current testing procedure only measures the viscous drag effects on the proppant. In addition, these factors are still not much understood, which leads to studies being done more on understanding these factors rather than remedying the laboratory testing procedure in the past several years (Aven et al., 2013).

In the case of test fluid, the API and ISO standards only mentioned 2% potassium chloride (KCl) in a deionised or distilled water solution as the test fluid. Although the standardisation is for a valid reason, it is an inadequate representation of real fracturing fluid. While the fracturing fluid has been one of the criteria in choosing proppant, this factor has mainly been based on the viscosity of the fracturing fluid to ensure good proppant transport (Zoveidavianpoor and Gharibi, 2015). This is because when the proppant has density similar to the fracturing fluid, this ensures a more ideal proppant distribution (Parker et al., 2012). The effect of the fracturing fluid on the proppant has been neglected, despite a recent increase in research on proppant diagenesis. The Dictionary of Petroleum Exploration, Drilling and Production defines proppant diagenesis as “the formation of crystalline material on uncoated ceramic proppants in an induced fracture in a high temperature, high pressure well, reducing fracture porosity and permeability” (Hyne, 2014). While proppant diagenesis has been around for quite a while, researchers have only recently found ways to test it. Proppant diagenesis may be the cause of the reduction in conductivity trend that has been observed when the proppant conductivity test is run over a longer period, such as in the observation by Penny (1987), Cobb and Farrell (1986) and Montgomery

and Steanson (1985). However, further understanding of proppant diagenesis is required for it to be implemented into conductivity test. Especially since LaFollette and Carman (2010) reported that the current laboratory test on diagenesis is inaccurate due to the excessively high temperature used in the haste to understand diagenesis.

In addition, additives in the fracturing fluids, such as a breaker, solid scale inhibitors, paraffin inhibitors, and polymer activators may further worsen the proppant diagenesis. There have been a few research works that studied the effects of additives on proppant conductivity, such as by Penny (1987), Bose et al. (2015) and Chauhan et al. (2019). However, they focused more on the positive effect of such additives on the proppant conductivity and not on the diagenesis effect that they may have on the proppant itself. For example, Bose et al. (2015) focus on the effect of breakers in reducing gel damage to improve conductivity, and the testing was performed only for a short-term conductivity.

The authors are also concerned about the fact that most diagenesis experiments were conducted under the influence of the fracturing fluid and not the producing fluid. This would be especially important in the case of coated proppant, specifically in the case of organic polymer coating. This is because organic polymers are easily subjected to the vagaries of the petroleum product (Graham and Sinclair, 1989; Zoveidavianpoor and Gharibi, 2015). In addition to that, it has been found that the effect of diagenesis was reduced in monolayer rather than multilayer proppants, which resulted in a more positive result (Gaurav et al., 2012). The results may also deviate more, as in real life it is almost impossible for the proppant to settle in monolayer in the formation (Brannon et al., 2004). Hence further research in the effect of diagenesis on proppant packing is necessary and is recommended.

Currently, there are also trends in using nitrogen gas as the test fluid, such as in procedures by Shekhawat and Pathak (2016) and Wen et al. (2013). The need is because HF is garnering more attention in stimulating gas reservoirs. According to Wen et al. (2013), the nitrogen gas was chosen for safety reasons and its similarity properties to methane gas. However, the authors were concerned about the insufficient comparative studies of these two types of fluids as the main test fluid, which may skew the result of the conductivity test.

In terms of the conductivity test cell itself, there are some design limitations that need to be addressed. Some of the concerns raised by Duenckel et al. (2016) are the proppant loading, sandstone core edge failure, the temperature control and the pressure distribution. The proppant loading is subjected to human error due to manual loading, so there is a need to design an automated proppant loading equipment in the future. The temperature and pressure condition was also seconded by Fernandes (2009). The sandstone core edge failure was a result of the

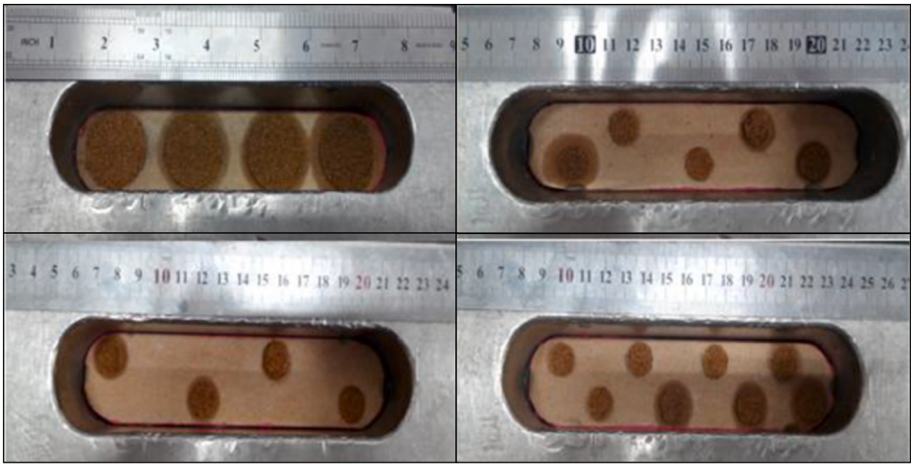


Fig. 18. Proppant distribution pattern (Hou et al., 2017).

Table 9
Limitations and disadvantages of API RP 19D.

Parameters	Limitation and Disadvantages	References
Effects measured	• Only viscous drag effect accounted for. • Multiphase effect, inertial effects of flow, proppant diagenesis, gel damage and many more not fully understood.	Economides (2009) ; Aven et al. (2013)
Test Fluid	• Limited to 2% KCl in DI water, no standard for gas fracturing fluid. • Lack of study on effect of fracturing and producing fluid on proppant. • Diagenesis was not accounted due to lack of understanding of diagenesis mechanism.	(RP19D, 2008) ; Zoveidavianpoor and Gharibi (2016) ; (Shekhawat and Pathak, 2016) ; Wen et al. (2013)
Conductivity cell	• Sandstone core edge failure. • Inaccurate temperature control. • Uneven pressure distribution.	Blair (2015) ; Duenckel et al. (2016) ; Fernandes (2009)
Human error	• Manual proppant loading leads to variation in proppant packing. • Ambiguous and simple instruction leads to big gap of interpretation in cell loading.	Duenckel et al. (2016, 2017)

stress exerted by the O-ring. [Duenckel et al. \(2016\)](#) proposed a few solutions to these predicaments, which will be discussed further in Section 4.3.

There are also rising concerns in the variation of proppant packing during conductivity testing resulting from human error. This is because, as pointed by [Liang et al. \(2015\)](#), conductivity is highly dependent on the grain size distribution and grain packing arrangement. This is supported by [Duenckel et al. \(2017\)](#), who found that 10-fold variation in permeability can be result from variation in the packing arrangement alone. While the API RP 19D cautioned the loader to evenly pour the proppant into the cell, the loose packing of the proppant resulting from such loading technique can easily shift with even a slight movement. This leads to a variation in the packing arrangement. In addition, the instruction for cell loading in API RP 19D is too simple and ambiguous,

leaving a big gap of interpretation. Hence leading to minute differences in cell loading from person to person.

In addition, the channel fracturing technique further adds to the need to revise the current testing standard. Currently, conductivity testing for channel fracturing has been conducted by modifying the proppant packing in the conductivity cell as shown in [Fig. 18](#). However, one particular study by Hou et al. (2017) shows that the proppant distribution pattern and mass affect the conductivity result. This proves that further research on the proppant distribution pattern is required. Depending on the result, there may be a need to regulate the proppant distribution pattern in proppant conductivity testing hereon. The limitations and disadvantages of the current conductivity testing standard are summarised in [Table 9](#).

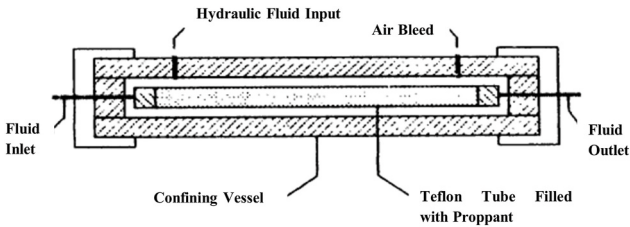


Fig. 19. Schematic of long-term permeability test cell (Cobb and Farrell, 1986).

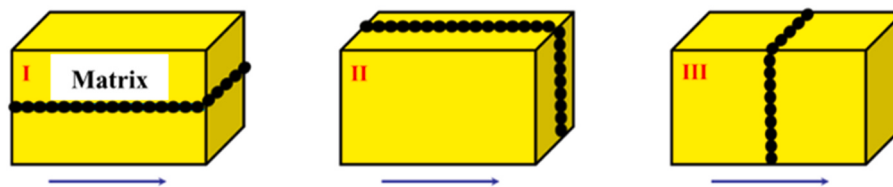


Fig. 20. Three basic fracture types (yellow rectangle represents rock matrix, black ball is proppant. The arrow is fluid flow direction) (Wen et al., 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

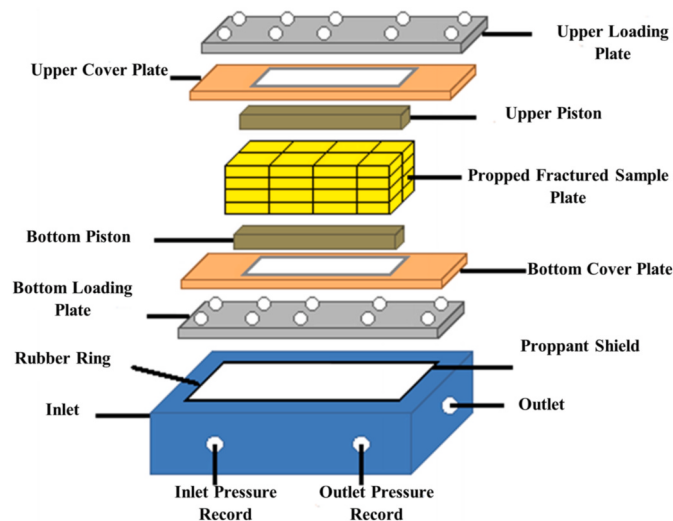


Fig. 21. Schematic of modified fracture conductivity test cell (Wen et al., 2013).

Table 10

Comparison between API and modified conductivity cells (Wen et al., 2013).

	Modified Conductivity Cell	API Conductivity Cell
End shape	Rectangular	Circular
Conductivity room	24.15 in	3.66 in
Volume		
Sample studied	Complex propped fracture network	Single propped fracture

4.3. Improvement and modification

Over the years, the advancement of proppant conductivity test technology and modification has varied with the intention of the researcher. Some researchers are more inclined towards immediate rectification of the current problem. Meanwhile, others are finding ways to include other factors that affect the conductivity of the formation,

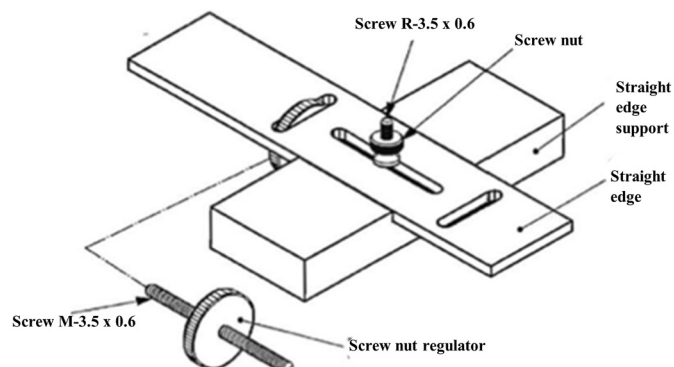


Fig. 23. Conductivity cell levelling device (RP19D, 2008).

such as the simulation of conductivity in multiple fractures. The modification may be in terms of conductivity test cell modification, testing condition or in the mathematical modelling of conductivity. This section will mainly focus on cell modification and the testing parameter.

One of the earliest cell modifications is by Cobb and Farrell (1986), who focus on the elimination of equipment corrosion problem. They incorporated Teflon, minimising the contact between the test fluid and the corrodible surface. The Teflon was used in such a way that it assembled the entire flow loop as shown in Fig. 19. While this changes the geometry of the proppant pack to a tubing geometry, Cobb and Farrell (1986) claimed that the result was similar to the previous efforts. However, their cell modification idea became obsolete with the development of guidelines by Penny (1987), which became the basis of API RP 61 for two reasons; the unconventional geometry and the solving of the corrosion problem by designing the cell with the corrosion-resistant 316 stainless steel.

Another modification that is worth taking note of is the cell modification by Wen et al. (2013). They proposed the modification to the conductivity cell that involved simulating multiple fractures as opposed to the current single fracture conductivity test cell. Their design is based on three basic fracture types as shown in Fig. 20. Fig. 21 shows the schematic of the modified cell proposed and Table 10 summarises the changes in comparison to the current conductivity cell. However, while these modifications were able to replicate the API standards with only an



Fig. 22. Damaged samples after applying closure stress (Wen et al., 2013).

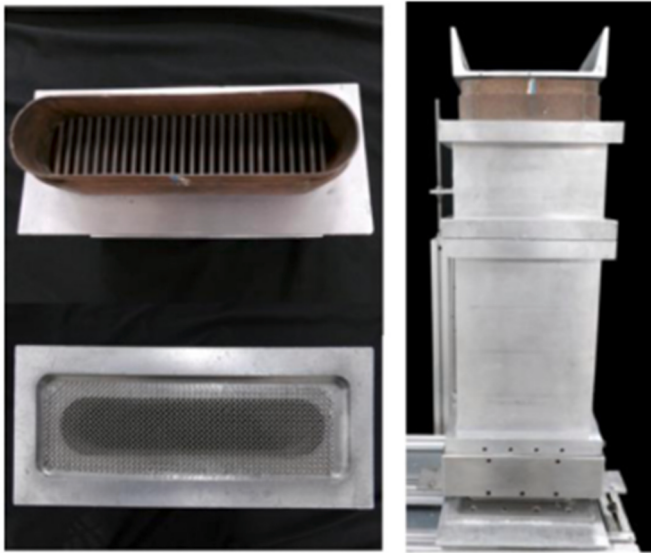


Fig. 24. Pluviator for conductivity cell (Duenckel et al., 2016).

8.1% error margin, this modification has one major flaw. The use of marble slabs due to the difficulties in acquiring shale rock was found not to be able to withstand the high-pressure condition during the testing and the slabs were damaged, as shown in Fig. 22. The damages may produce fines, which leads to blockages and thus reduces the actual proppant conductivity.

By far, the current most noteworthy modification is by Duenckel et al. (2016), who focused more on the immediate rectification of the issues raised mentioned in Section 4.2. The first improvement suggested by Duenckel et al. (2016) was in terms of loading the proppant into the cell. They supported the implementation of the conductivity cell levelling device (Fig. 23) in API to allow even pouring of the proppant and suggested the addition of pluviator (Fig. 24) to increase consistency in cell loading. The idea came from the extensive development of crush cell for crush resistance testing. However, a recent study by Richard et al. (2019) found that this levelling device may not be sufficient. The loose

packing of the proppant leads to rearrangement with even a slight force. In this study, the authors suggested a vibrational technique to reduce proppant pack variance, which has shown a positive result for homogenous ceramic proppant. However, further research is still required as this vibrational technique can lead to the segregation of material for proppant with non-uniform gradation, especially in sand proppant.

Next, Duenckel et al. (2016) proposed to bring back the steel shim from API RP 61. This is in line with Blair (2015) suggestions, who reported that the reduction of conductivity test readings is due to proppant embedment and production of fines resulted from the use of soft sandstone core. However, this contradicts to the findings by Penny (1987), who states that the embedment needs to be included in the testing to replicate the phenomenon occurring in the formation. Neglecting this factor may cause further deviation between the results between the laboratory testing and actual practice. Duenckel et al. (2016) considered

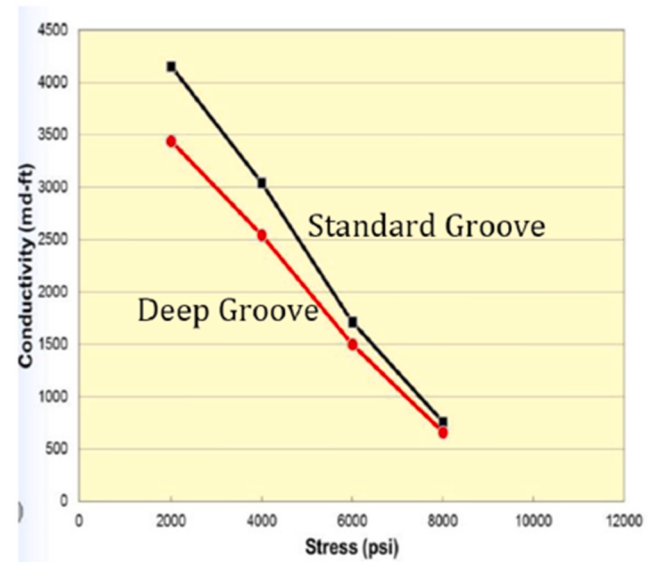


Fig. 26. Standard vs deep groove (Duenckel et al., 2016).

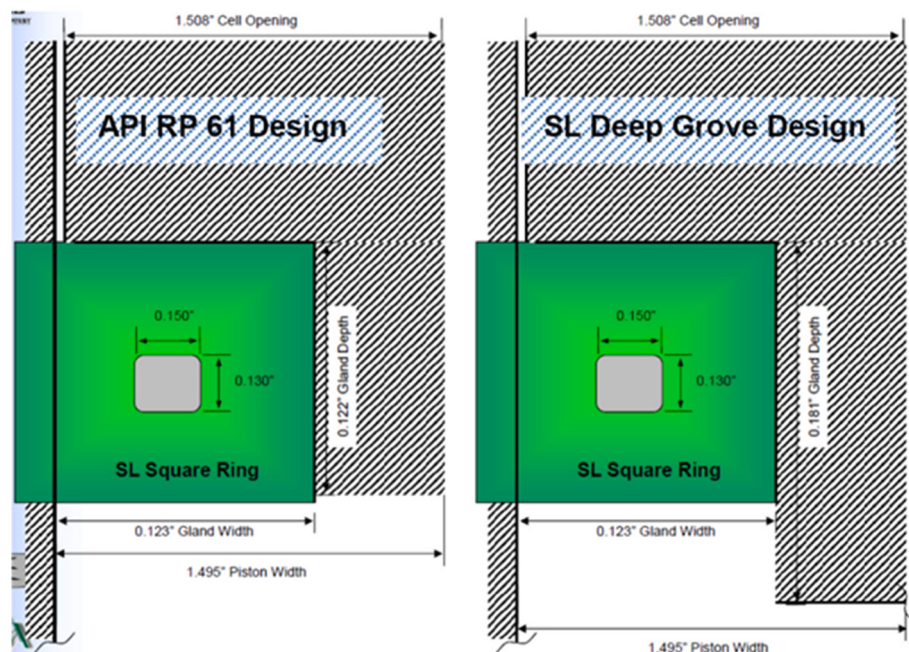


Fig. 25. Deep groove design (Duenckel et al., 2016).

Table 11
Summary of studies on proppant conductivity test.

Reference	Aim	Studied Parameter(s)/Modification(s)	Findings
Cobb and Farrell (1986)	Cell modification for elimination of equipment corrosion by Teflon coating.	Teflon coating were incorporated in tubular geometry as in Fig. 19.	Conductivity results were in line with previous API testing.
(Wen et al., 2007)	To study the effect of proppant embedment on proppant conductivity.	- Comparison of conductivity between using sandstone and steel platen using the standard API cell as in Fig. 16. - Proppant concentration was also varied.	- Better conductivity in steel platens over sandstone platens experiment shows lack of embedment in steel platens. - Embedment in sandstone platens only pronounce at a certain pressure subject to proppant concentration. Embedment caused conductivity decrease (65.9% and 87.5% respectively at proppant concentration of 10 kg/m² and 5 kg/m².
Wen et al. (2013)	Cell modification to investigate on multi fracture conductivity.	Cell modification as in Fig. 21 with three basic fracture geometry as in Fig. 20.	- Modified test cell was in line with API standard cell with deviations ranging from 4.4% to 8.1%. - Impact factor of fracture type in propped fracture network conductivity: Type-II > Type-I > Type-III (insignificant factor) - Increase number of fractures increases propped fracture network conductivity
Blair (2015)	To study effect of cell loading technique on fracture conductivity testing.	- Injection technique: - Hooke cylinder (Fig. 27). - Narrow mouth wash bottle (Fig. 28). - Vibration technique using sieve shaker (Fig. 29).	- Hooke cylinder failed to transport proppant due to misfit fittings and tubings. - Guar gum contamination (from usage as carrier fluid during cell loading) significantly impact conductivity rendering NMWB not suitable for comparison study. - Vibration technique produces similar result to API standard method but with overall lower variance.
Duenckel et al. (2016)	Design modification of conductivity cell for best practice.	- Cell levelling device (Fig. 23) and pluviator (Fig. 24) were incorporated during cell loading. - Incorporation of steel shim in between sandstone core and the upper and lower piston. - Deeper seal ring/piston groove (Fig. 25) - Reposition the thermostat to cell outlet.	- Cell levelling device and pluviator helps ensure the proppant loading is constant. - Steel shim reduces sheer failure on the edges of the sandstone. - Deeper seal ring/piston groove reduces width measurement uncertainties. - Repositioning the thermostat reduces temperature detection error.
Shekhawat and Pathak (2016)	Conductivity measurement through newly developed set-up.	- Test fluid: Nitrogen - Cell modification (refer Fig. 30): - Radial geometry. - Material: Mild steel. - Temperature: Ambient. - Incorporate Teflon sheet.	- New set-up able to concurrently measure permeability alteration, conductivity, fracture width reduction and fluid flow reduction rate allowing on-site testing. - Sudden drop of conductivity above 550 bar shows monolayer packing unsuitable above this pressure due to proppant crushing.
(Ereaux, 2017)		- Vibration loading technique using: - Vibration Test Machine (VTM) (Fig. 31). - Sonochemical Reaction Vessel (SRV) (Fig. 32).	- VTM reduces conductivity variance but deemed unsuitable due to difficulty in applying constant amplitude. - Compared to Blair (2015), SRV reduced the variance of conductivity results by 70%–90% despite lower conductivity compared to standard API method.
Richard et al. (2019)	Development of a new conductivity cell loading process.	- Integration of vibration techniques using SRV: - SRV Method 1 uses unmodified API cell. - SRV Method 2 uses modified API cell.	- Vibration technique reduces conductivity variance with average variance at 6% in SRV Method 1 and 11% in SRV Method 2 compared to 31% in standard method. - Weakness: segregation of material for particles with non-uniform gradation.

this and, instead of entirely substituting the sandstone core as suggested by Blair (2015), they suggested placing the shim in between the sandstone core as well as on the upper and lower piston. This reduces the sheer failure that causes damage on the edges of the sandstone as the stress is transferred to the steel shim. The high strength of the steel sheets would allow for a wider area distribution of stress on the sandstone core, reducing the probability of damage.

Duenckel et al. (2016) also proposed a modification to the seal ring/piston groove, as shown in Fig. 25. The deeper groove removed uncertainties with width measurement, which affect the conductivity correlation. This is supported by Mattson et al. (2014), who found that the current design of rectangular square ring resulted in a non-uniform stress field across the proppant pack and a rearrangement of the proppants toward the middle of the proppant pack in the standard Cooke cell. The deep groove design modification may be able to overcome this. The difference between the results of deep groove design and the standard is apparent as shown in Fig. 26. The resulting conductivity was reduced

due to the more uniform distribution of stress from the piston to the proppant pack. Hence further reducing the damage to the edges of the platens.

The next modification proposed by Duenckel et al. (2016) is the position of the thermostat to detect the temperature in the cell. Temperature not only plays an important aspect due to the dependency of the viscosity on it, but is also an important factor in the calculation of the flowrate. Duenckel et al. (2016) found that there is a temperature drop across the proppant pack. However, when the thermostat is placed on the inlet, the drop in temperature below the API RP 19D requirements was not detected. Hence it was proposed to place a thermostat at the outlet to eliminate this error. The authors find that Duenckel et al.'s (2016) proposal was the closest to achieve better conductivity testing accuracy and is sustainable for immediate implementation. It reduces the uncertainty and increases the accuracy of conductivity testing, as implemented in Stim-Lab. However, this has not been tested with nitrogen gas as the testing fluid, which is the current trend, so more studies



Fig. 27. Hooke cylinder (Blair, 2015).

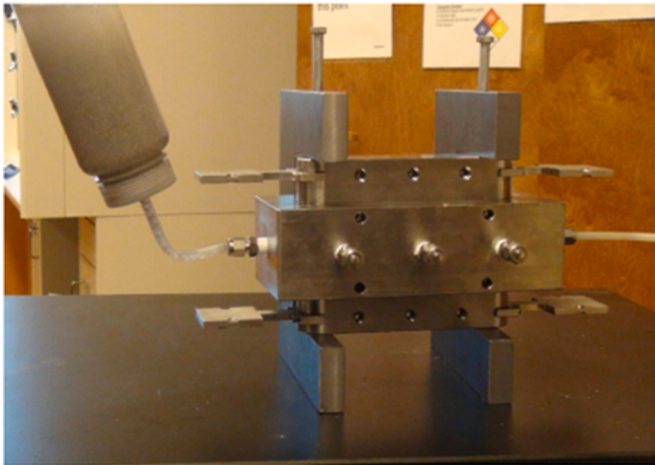


Fig. 28. Narrow mouth wash bottle hooked to conductivity cell (Blair, 2015).

are required. Table 11 summarises the modification done to proppant conductivity testing over the years.

5. Proppant transport

Proppant transport plays a vital role in the success of HF operation. Poor proppant transport leads to poor proppant settlement, as it leads to early settlement of proppant at the lower region of the created fracture. This results in shorter effective fracture length and inadequate coverage of the productive zone's total height ((Economides, 2009). Inadequate

cleanup of the resultant propped fracture may also damage the proppant pack. Hence may considerably reduce the conductivity of the fractured area.

Since the proppant transport has been recently reviewed critically by Sahai and Moghanloo (2019), the earlier studies will only be briefly covered. Originally, the proppant transport was evaluated in laboratory by using the vertical slot model developed by Kern et al. (1959). The early studies focused on the mechanism of proppant transport in single fracture using this slot model. Some of the earlier studies includes, but not limited to proppant build up (Schols and Visser, 1974), fracture roughness (McLennan et al., 2008) and proppant holdup (R. D. Barree and Conway, 2001). However, the vertical slot model developed by Kern only studied single fracture.

Even though the fractures formed are usually complex, the studies into complex fracture only started in 2009 by Dayan et al. (2009) with a small-scale fracture model. Later, Sahai (2012) continued the studies with a larger modified model as shown in Fig. 33. Plexiglas sheets of equal length was used to create the complex fracture inside the Plexiglas frame with four different slot configurations as shown in Fig. 34. Wen et al. (2016) carried similar studies, varying the length of the primary and secondary slots from the inlet. Their studies found that the closer the secondary fracture to the wellbore, the higher the propped height and propped area in the secondary slot. However, both Sahai (2012) and Wen et al. (2016) assumed the intersection of the fractures to be 90° which does not truly represent the natural fractures occurring in HF. Thus, N. Li et al. (2016), and Tong and Mohanty (2016) continued the work by varying the angles of the intersection. Though, the works by Tong and Mohanty (2016), despite extending the angles more than 90°, the reciprocated angles show similar results with works by N. Li et al. (2016). Nevertheless, the surface of Plexiglass is smooth and thus these models lack the surface roughness that are present in natural fractures. Later works showed that surface roughness results in fairly non-uniform proppant placement and can affect the aperture sustainability and fracture conductivity (Alotaibi and Miskimins, 2015; Huang et al., 2017; Raimbay et al., 2016).

The laboratory testing of proppant transport after the year 2017 is quite scarce. This could be due to more focus on numerical and CFD modelling of proppant transport instead for efficiency and cost

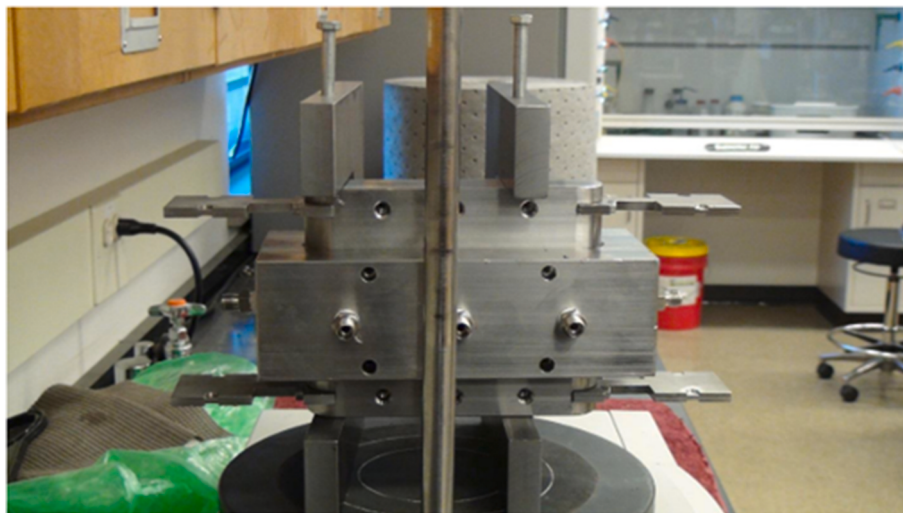


Fig. 29. Conductivity cell clamped on sieve shaker (Blair, 2015).

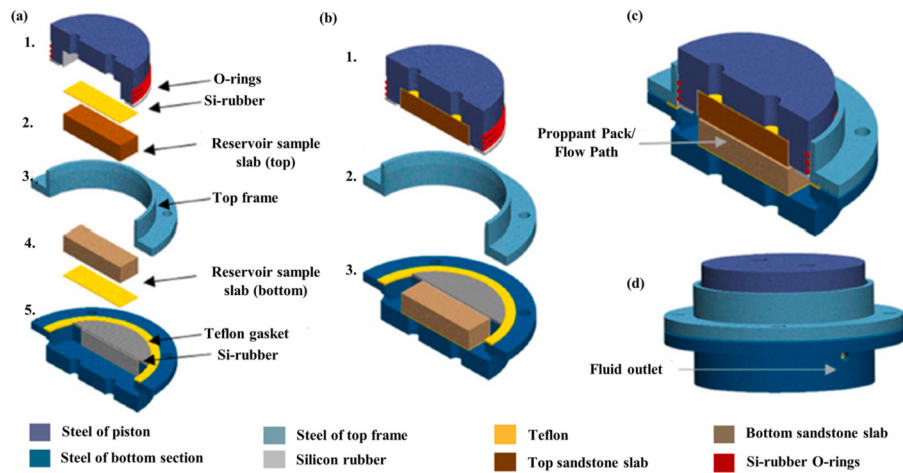


Fig. 30. Central cell assembly (a) exploded cross-sectional view 1. Piston 2. Top rectangular slab of reservoir rock 3. Frame 4. Bottom rectangular slab 5. Bottom section, (b) cross-sectional view 1. Piston with top slab 2. Top frame 3. Bottom Section with lower, (c) Cross-sectional view of assembled central cell, (d) Central cell (Shekhawat and Pathak, 2016).

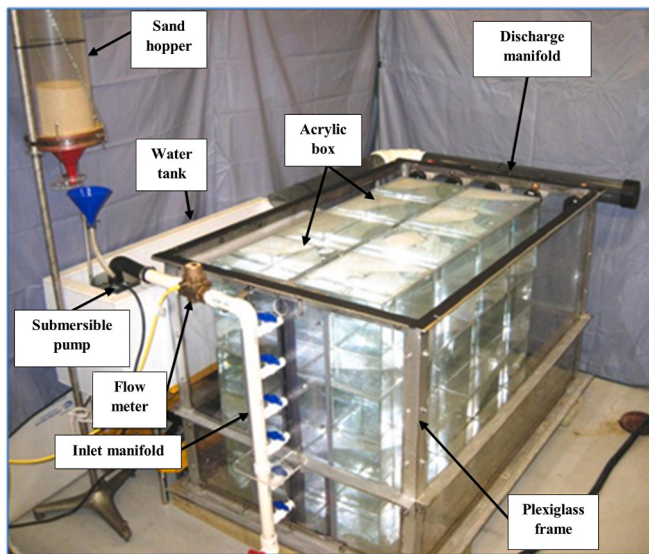


Fig. 33. Modified vertical slot for complex fracture (Sahai, 2012).

effectiveness. It is interesting to see the modification of laboratory set-ups shifted to accommodating other fracturing fluids such as foam and slickwater. Tong et al. (2018) studied the proppant transport in foam fracturing fluid. They designed a slot to visualise the process of proppant transport using a Hele-Shaw slot (Fig. 35). The studies focus more on the effect of the quality of foam towards the proppant transport and found that proppant is transported better in dry foam as compared to wet foam. There is little to no vertical settling in dry foam while in wet foam, the proppant tends to settle early near the fracture entrance.

On another note, the proppant transport in slickwater studies by Chun et al. (2020) features an inclined slot since it is mostly applied in horizontal drilling. Like the previous models, this vertical slot uses Plexiglass for ease of visualisation. Fig. 36 shows the schematic diagram of the inclined slot. In inclined proppant transport, frictional force become more prominence at dictating the mechanism of transport as the inclination reaches close to horizontal. While the proppant distribution is wider, the dune area is smaller as result of the thin suspension area

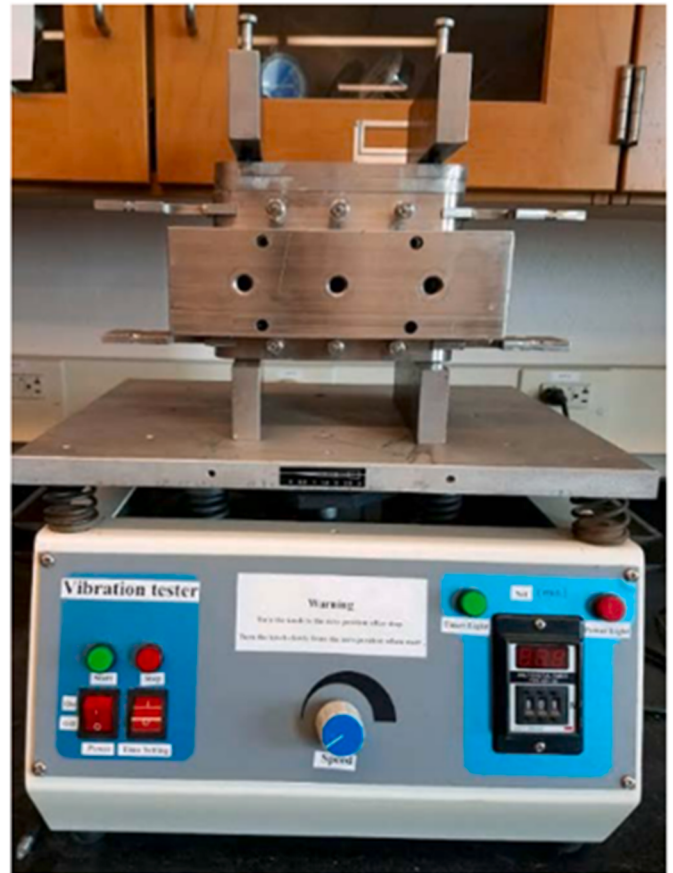


Fig. 31. Conductivity cell attached to VTM (Ereaux, 2017).

produced which is not present in vertical slot. The effect is more considerable in proppant of smaller size.



Fig. 32. Conductivity cell attached to SRV (Ereaux, 2017).

6. Proppant erosion and flowback

6.1. Background

Proppant erosion posed a huge problem in HF. It causes damages to both the equipment and the formation, especially in the case of perforation completion, which is a growing trend in HF. It is worsened by proppant flowback in which up to 20% of the proppant could return to the surface, leading to an increase in labour and costs to manage it (Card

et al., 1995). Proppant flowback problem is found to be worst in the gas/water mixture condition. While there has been extensive research in particle erosion in general, the mechanism of proppant erosion is still not fully understood (Vincent et al., 2004). This is especially true in coated proppant. While the coatings improved the angularity of the proppant, it has been found that it can increase the erosion by 15 times. This may be attributable to static charges (Vincent et al., 2004).

In general, the method to test for proppant erosion can be divided into three categories; mechanical methods, empirical methods, and computational fluid dynamic (CFD) modelling methods (Yuan et al., 2017). In this section, the empirical and CFD methods will only be briefly discussed as the authors will focus more on mechanical methods. There are no standards assigned specifically for proppant erosion testing. However, there are many documented general erosion standards that either exists as a standalone, such as ASTM G76-18 and ASTM G211-14, or as part of other systems' recommended practice, such as API RP 14 E.

One of the most commonly practised mechanical methods is the particle impingement test. As the name implies, the erosion is assessed based on the loss of weight of the specimen when subjected to repetitive impact of the projected particles (i.e., proppant) onto the surface of the specimen. The projectile media can either be gas, as in ASTM G76-18, or slurry, as in ASTM G75-15. Although the guideline has been strictly defined, it still provides flexibility in terms of set-up design and the testing parameters (i.e., impact velocity and angle), provided the changes are stated clearly. In terms of a testing device for gas impingement testing, the general set-up, as described in ASTM G76-18, consists of four major parts: a nozzle, a mixing chamber, a source of compressed air and an abrasive metering system, which has remained mostly the same throughout the years. Most modifications done are minor, such as on the loading mechanism or the improvement in compression system to allow higher velocity of the particle.

Studies on the improvement and modification of erosion testing device are scarce and the earliest design that the authors could find is the room temperature erosion tested used by Lapides and Levy (1980) as depicted in Fig. 37 and Fig. 38. Lapides and Levy (1980) claimed that

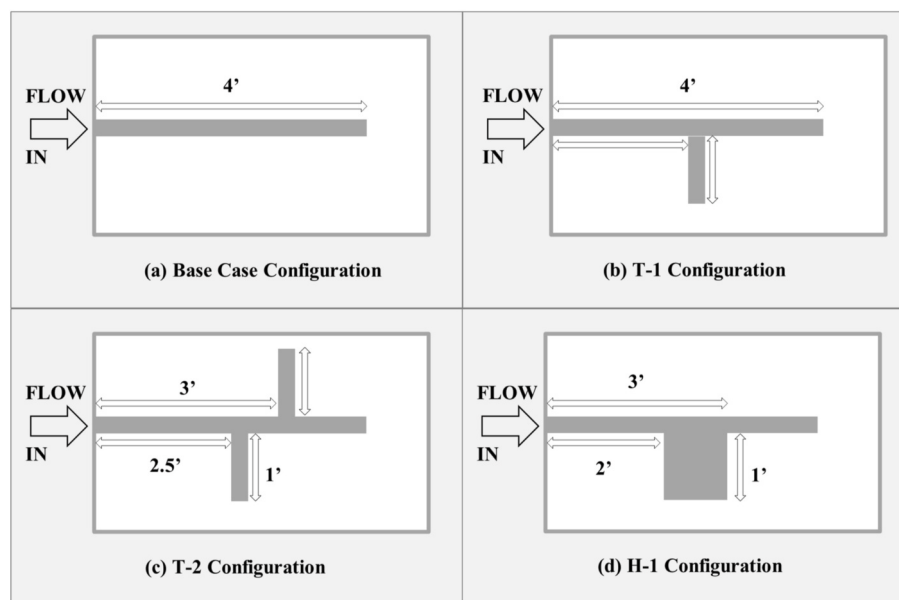


Fig. 34. Schematic diagrams of the four different slot configurations – Top view (Sahai, 2012).

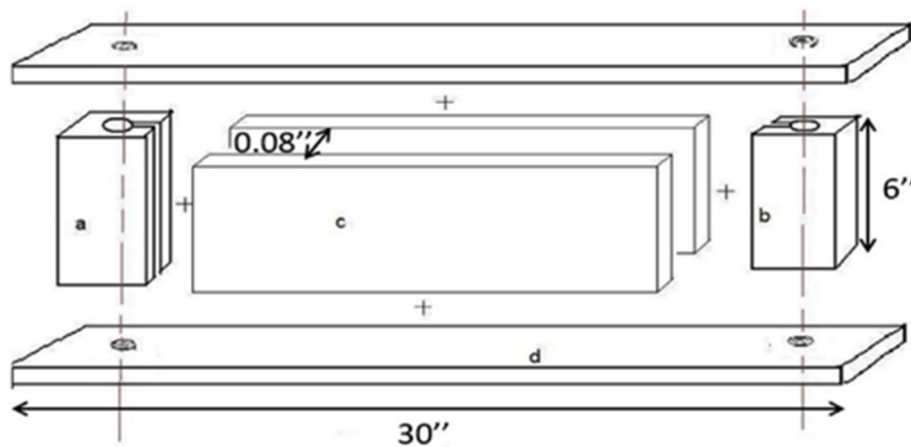


Fig. 35. Schematic diagram of Tele-Shaw slot (Tong et al., 2018).

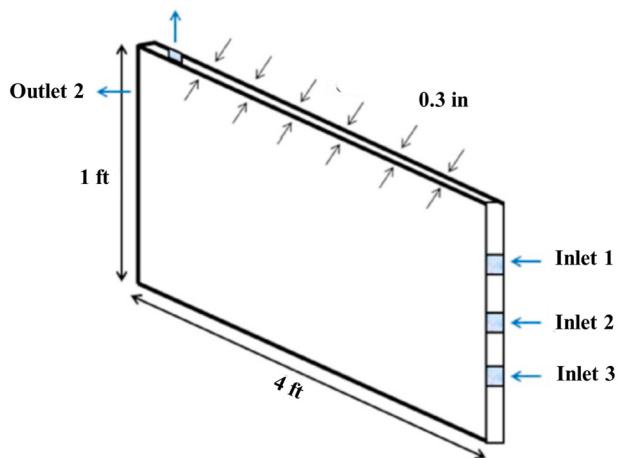


Fig. 36. Schematic of the dimensions of a fracture cell used in the experimental study having three inlet points and two outlet points (Chun et al., 2020).

this device is basically a modification of an erosion testing device originally developed by Sheldon in 1965. The design was modified with ease of operation in mind and with the addition of velocity measurement, where a vibratory feed mix is used to ensure a uniform particle

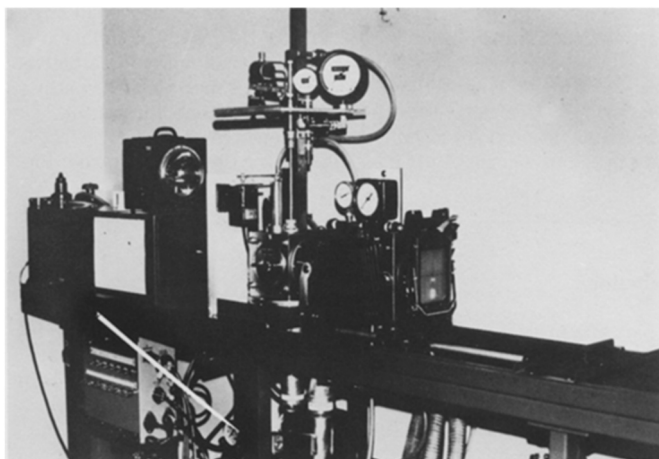


Fig. 37. Room temperature erosion tester (Lapides and Levy, 1980).

distribution and the particles are propelled via gas. The alteration in the pressure drops across the nozzle controls air and particle velocity.

As for slurry testing, Buszko and Krella (2017) has written a good critical review on existing devices. While ASTM G75-15 is useful in evaluating the durability of the metal alloys used in frac pumps, the authors are concerned that this may be insufficient as it only concerns the slurry's abrasivity. In addition, many other researchers use other existing devices (Buszko and Krella, 2017). The devices can be summarised into two categories: the jet type and the rotating type. The design for jet type in ASTM G73-10, consist of the impeller system (Fig. 39) to pump the slurry and a nozzle to direct the slurry. However, this method may pose the risk of damage to the pump due to the impact of the solid particles on the rotor blades at different velocities. In ASTM

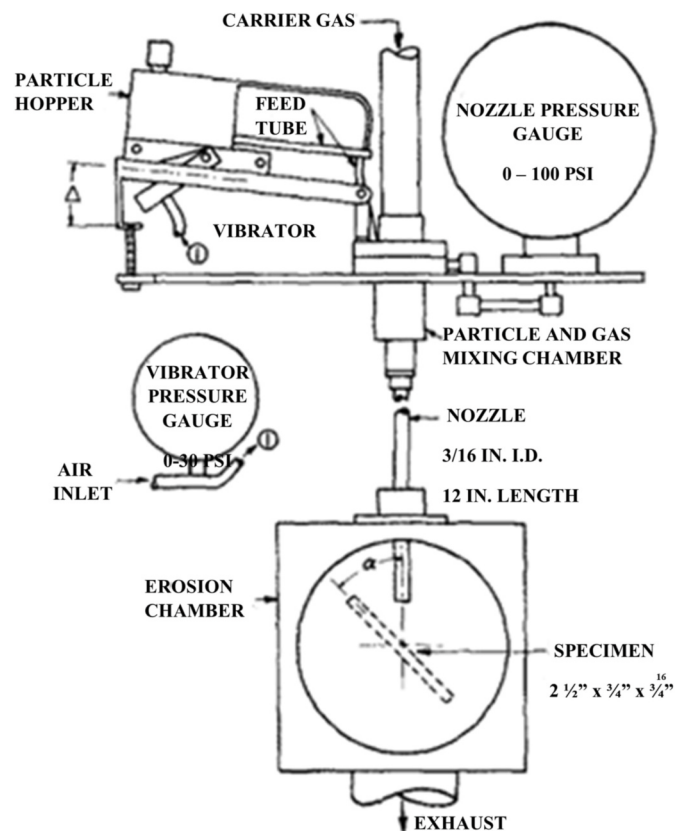


Fig. 38. Schematic diagram of room temperature erosion tester (Lapides and Levy, 1980).

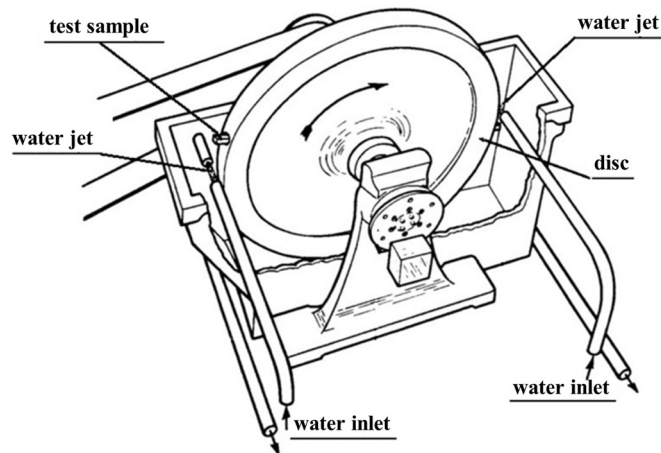


Fig. 39. Rotating disk and jet repetitive impact apparatus (ASTM G73-10, 2017).

G76-18, a gravitational delivery system (Fig. 40(a)) was used which reduced the risk of damage on pump but the velocity achieved is lower than in ASTM G-73-10. Therefore, the use of an ejector to propel the slurry has been proposed (Fig. 40(b)). This device design prevents erosion of the pump but the amount of erodent impacting a specimen is related to the fluid velocity and the pressure fall in the ejector.

The rotating type can be divided into three separate types; the slurry pot, the Coriolis, and the whirling arm (Buszko and Krella, 2017; Grewal et al., 2013). The slurry pot testing device introduced by Tsai et al. (1981) has a very simple design as shown in Fig. 41. It consists of a propeller, a shaft and four test specimens. The propeller allows uniform distribution of the solids in the liquid medium, while the shaft protects the propeller against falling solid. The design allows simultaneous testing of up to four specimens, and the simplicity makes it easy to manufacture at low cost. However, the flow conditions and the parameters of the particles are very hard to control (Gadhikar et al., 2011).

Introduced in 1984 by Tuzson (1984) and later modified by Clark et al. (1999), the Coriolis testing device utilises centrifugal and Coriolis forces as shown in Fig. 42. The slurry is placed into the slurry inlet pot located on the centre of the rotor and the specimens are placed equidistance on either side of the Coriolis. The centrifugal force accelerated the slurry outwards, which causes the erodent particles to settle on the surface of the test specimen under Coriolis force. The high rotation speed leads to shorter testing time. Lastly, the whirling arm test device (Fig. 43), developed by Lin and Shao (1991) consists of a slurry tank where a

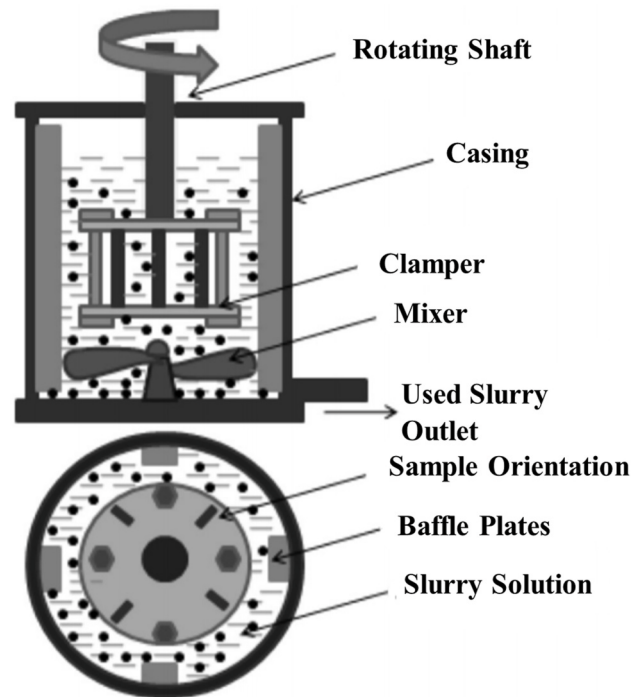


Fig. 41. Slurry pot test device (Thakur and Aurora, 2013).

mixture of solid and water are mixed using a stirrer. The mixture then flows into the next tank. The slurry then falls onto the test specimens, which are held in each of the test device's four arms and moves in a rotation. This testing device features fine adjustment of the impact angle and impact velocity. The later modification by Abouel-Kasem et al. (2010) and Al-Bukhaiti et al. (2007) also eliminated the effect of airflow (aerodynamic effect) on the slurry stream by conducting the test in vacuum. Table 12 summarises the devices used in the impingement erosion test.

In terms of empirical method, a few models have been proposed and summarised in Table 13. These models are based on the ductile materials erosion theory. The mechanism of erosion in each model varies, depending on the condition of the particle that is eroding the surface. This includes the shape of the particles, the temperature of the testing

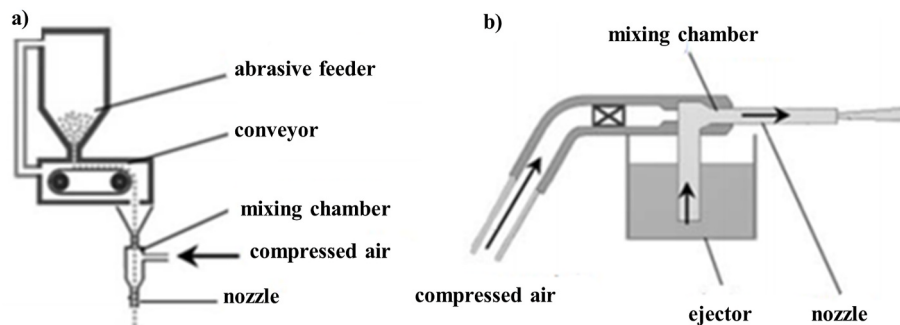


Fig. 40. Examples of the slurry jet devices with various dosing systems, (a) abrasive delivered by gravity, (b) with using an ejector (ASTM G76-18, 2018).

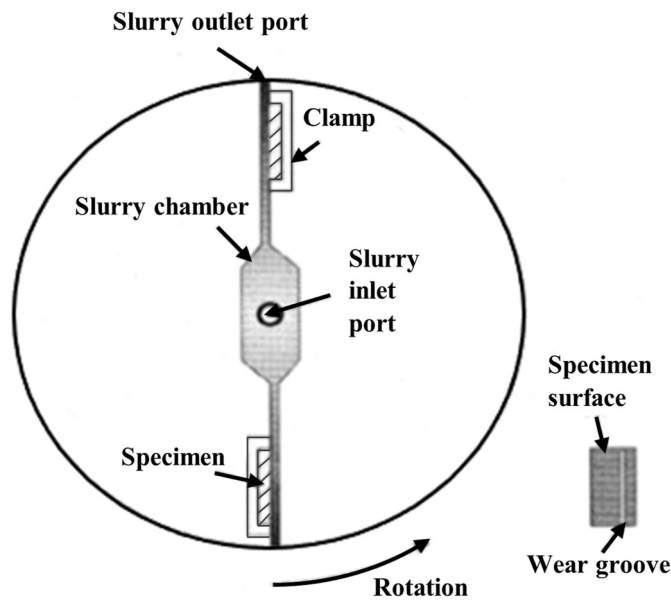


Fig. 42. Coriolis erosion tester (Clark et al., 1999).

condition, the driving functions, and the final condition of the particle, whether they are still intact after impact or break into fragments. However, in most of the models, the velocity of the particles has major importance in the erosion rate.

While mechanical methods like impingement test are more popular in lab-scale testing, CFD modelling (Fig. 44) has been gaining more attention for field practice. This is because it provides timely and cost-effective results (Clem et al., 2006; Li et al., 2005; Messa and

Malavasi, 2018; Yuan et al., 2017). The results are also more accurate to the real field operation. The CFD modelling is usually computed based on well-known empirical models, such as the Erosion model and Oka erosion model, which is usually coupled with mixed Euler-Euler approach or the Euler-Lagrangian approach (Messa and Malavasi, 2018; Oka et al., 2005; Oka and Yoshida, 2005; Yuan et al., 2017). The Lagrangian framework is very useful in the prediction of the influence of the particles on the fluid flow (two-way coupling interactions) and particle-particle collisions as well as contacts (four-way coupling interactions), but it demands a high computational cost and neglects particle-particle interaction and accumulation of the entrained particles. On the other hand, the mixed Euler-Euler approach provides a faster result at a more cost-effective method compared to the Euler-Lagrangian approach (Messa and Malavasi, 2018). The Euler-Granular approach has a high potential in complex prediction of full-scale erosion but the computational demand is higher than the two other approaches (Lu and Agrawal, 2012; Tong and Mohanty, 2016). Table 14 summarises the CFD modelling used in the prediction of erosion behaviour.

6.2. Limitation and challenges in proppant erosion evaluation

The main challenge in proppant erosion studies is the lack of understanding of the full mechanism of erosion (Yuan et al., 2017). Despite hundreds of years of research into frictions and abrasion, the mechanisms of erosion are still debatable even when it is limited to proppant erosion. The theory varies from one researcher to another. These ranges from the cutting wear or micro machining theory (Finnie, 1960) to the loss of material theory, either by being swept away by the particle's radial flow (Sheldon and Kanhere, 1972) or attachment to subsequent particle's rebound (Vincent et al., 2004). Yet, most of these theories are based on ductile material.

There are many factors that affect the erosion of proppant. This includes the type and characteristics of proppant, the rheological and flow characteristic of the carrying fluid and the velocity and trajectory of the impact. Despite the greatest consensus that the jet impinging method is

Table 12
Summary of impingement erosion testing device.

Design	Device	Media	Description	Advantage	Disadvantage	Reference
Jet type	Gas impingement (Figs. 37 and 38)	Gas	Based on design by Sheldon in 1965 with addition of vibratory feed mix, ensuring uniform particle distribution.	• Simple and easy to use design.	• N/A	Lapides and Levy (1980)
	Rotating disk (Fig. 39)	Slurry	Slurry pump using impeller system and nozzle direct the slurry at rotating or stationary specimen or target.	• High velocity can be achieved.	• Risk damaging pump due to solid particles impact on the rotor blades.	ASTM G73-10, Buszko and Krella (2017)
	Gravitational delivery system (Fig. 40 (a)) Ejector (Fig. 40 (b))	Slurry Slurry	Uses compressed air to propel slurry to target. Uses ejector to propel slurry to target.	• Prevents pump against erosion. • Prevents pump against erosion.	• Low velocity of propelled slurry. • Amount of erodent impacting a specimen is related to the fluid velocity and the pressure fall in the ejector.	Buszko and Krella (2017), ASTM G76 Buszko and Krella (2017), ASTM G76
Rotating type	Slurry Pot (Fig. 41)	Slurry	Solids in the liquid medium are uniformly distributed by propeller which then eroded the four test specimens held at the shaft which is rotated by the attached motor.	• Allows conducting of four simultaneously testing.	• Hard to control flow conditions and the parameters of the particles.	Buszko and Krella (2017), Tsai et al. (1981), Grewal et al. (2013), Gadhikar et al. (2011)
	Coriolis (Fig. 42)	Slurry	The centrifugal force accelerated the slurry located in the slurry pot outwards, causing erodent particles to settle on the surface of the test specimen under Coriolis force.	• Testing time is shortened.	• N/A	Tuzson (1984), Clark et al. (1999)
	Whirling arm (Fig. 43)	Slurry	Consist of a slurry tank in which a mixture of solid and water are mixed using a stirrer. The mixture then flows into the next tank. The slurry then falls down onto the test specimens which are held in each of the test device four arms and moves in a rotation.	• Able to fine tune impact angle and impact velocity. • Vacuum condition eliminates the effect of air flow.	• Requires proper mixing of the erodent mixture.	Lin and Shao (1991), Abouel-Kasem et al. (2010), Al-Bukhaiti et al. (2007)

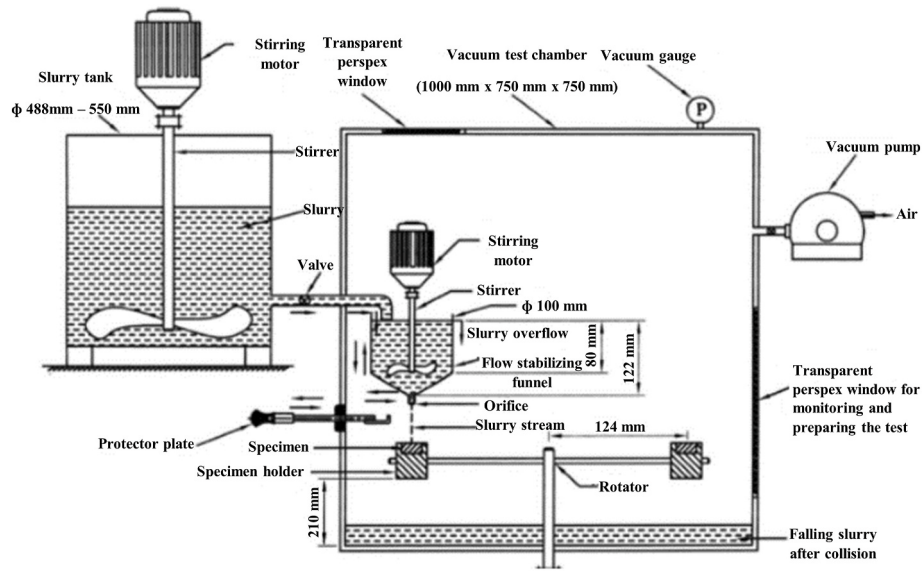


Fig. 43. Schematic diagram of whirling arm test device (Buszko and Krella, 2017).

dependent on impact velocity and angle, consistent erosional testing resulting from various research works was still failing to be achieved (Oka et al., 2001). They argued that this occurs due to the lack of understanding of the condition of the particle impact in their erosional facility. Particularly, the effect of fluid velocity and insufficient particle inertia in validating the impact velocity and angle was overlooked.

Moreover, Yuan et al. (2017) argued that mechanical testing is a poor depiction of real field condition as it heavily relies on the specific experimental condition. Variations in fluid properties, such as fluid density, viscosity and composition were also neglected. The experiment system was considered as isolated, and the results are limited to the parameters selected. Again, the lack of understanding of erosion is the

Table 13
Erosion model.

Reference	Aim	Assumption	Equation
Finnie (1960)	Particle cutting erosion wear model.	- The impact particle is harder than the target surface and does not breakup. - Material is removed in a same way as removed by a single point cutting tool.	Volume of surface material removed = area swept out by particle tip x width of cutting face
Sheldon and Kanhere (1972) (Tilly, 1973)	Study of impingement erosion process by investigating the effect of impact of relatively large single particle on an aluminium surface. Study of two stage erosion process.	Material removed is related to the depth of penetration of the particle.	$E_m \sim q^3 = \frac{d^3 V^3 (\rho_p)^{3/2}}{H_v^{3/2}}$
(Jennings et al., 1976)	Erosion based on an identified erosion mechanism i.e. Target melting.	In secondary erosion, erosion occurs only when the particles break up on impact and the amount of erosion is proportional to the initial kinetic energy and the level of fragmentation.	$E = \hat{E}_1 \left(\frac{V}{V_r} \right)^2 \left[1 - \left(\frac{d_0}{d} \right)^{3/2} \frac{V_0}{V} \right]^2 + \hat{E}_2 \left(\frac{V}{V_r} \right)^2 F_{d,v}$
		- Resistance to melting: Density, thermal conductivity, melting temperature, enthalpy of melting and molecular weight of target material. - Physical nature of erodent particles: roundness. - Driving functions: Kinetic energy transferred to the target by the impacting particles.	$E_v = \left(\frac{K_T^{5/2}}{R} \frac{G^{1/3}}{\rho_t^{1/3} k T_m \Delta H_m} \right) S$
(Hutchings, 1981)	Erosion at normal incidence by platelet formation.	Target material is struck by a large number of spherical projectiles, each travelling at same velocity and causing same pattern of plastic deformation.	$E = 0.033 \frac{\rho_p \sigma^{1/2} V^3}{\epsilon_d^2 p^{3/2}}$
(Sundarajan, 1991)	Emphasized on the correlation that exists between the plastic zone size and the erosion rate.	Plastic zone was proportional to the diameter of the crater formed by the impact of one particle.	$E \approx L^3 \left(\frac{\Delta \epsilon_m}{\epsilon_c} \right)$
Oka and Yoshida (2005)	Estimation of erosion damage caused by solid particle impact.	Effective parameters: impact velocity, angle, size and type of particles (particle property) and material hardness.	$E = g(\alpha) E_{90}$
(Siddhartha, 2013)	Developed for the prediction of erosion wear rate.	- Erodent particle is rigid and does not deform during impact. - The problem treated as quasi-static i.e. Dynamic effects such as wave propagation is neglected. - Strain rate sensitivity is neglected. - The only force assumed to be contact force exerted by the surface. - Erodent particles are square pyramidal in shape.	$E_{90} = K(aHv)^{k_1 b} \left(\frac{v}{v} \right)^{k_2} \left(\frac{D}{D} \right)^{k_3}$ $E = \frac{1}{6H_v} \times \eta \times \rho_t \times V^2 \times \left(\frac{2A \sin \alpha \cos \varnothing + 3h \cos \alpha}{A \sin \alpha \cos \varnothing + h \cos \alpha} \right)$

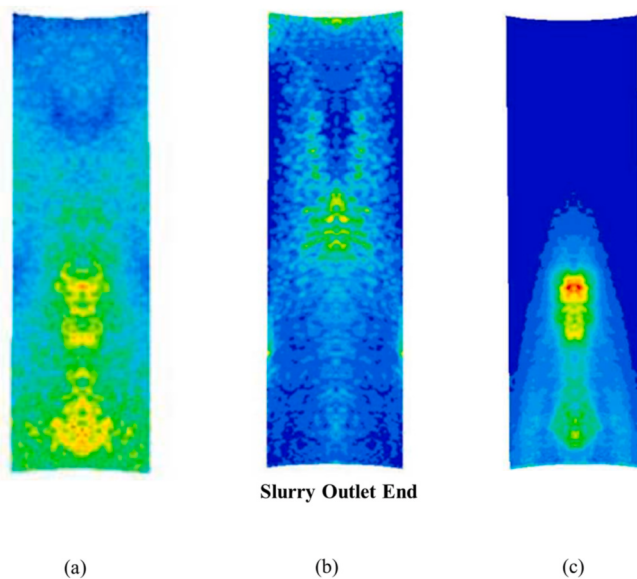


Fig. 44. Example of CFD modelling. Distribution of (a) particle impact velocities, (b) angles and (c) erosion depth on the inside surface of upper extension sleeve at 15 bbl/min flow rate (0.40 vol fraction of proppant) (Li et al., 2005).

cause of this underdevelopment of current erosion testing.

7. Conclusions

This paper briefly reviewed the current standard procedure in testing proppant characterisation, conductivity, transportation, and erosion. The key findings of this review can be summarised as follows:

- The emergence of unconventionally shaped proppants calls for the revision of API RP 19C in terms of proppant sphericity and roundness as these newly shaped proppants does not conform to the aspects of the standard.
- While the established API RP 19D remains the best current standard procedure for testing proppant conductivity, it still needs to be improved to accommodate other factors, such as the multiphase effect, inertial effects of flow, proppant diagenesis, and gel damage, that could affect the conductivity result.
- With the recent advancement in proppant diagenesis research, a new procedure for testing coated proppant, or modification to accommodate this, may need to be studied. This is because the long-term coating behaviour (mechanical strength, thermal stability and degradation and effect on diagenesis) under high temperature and pressure affects the conductivity of the proppant.
- Further studies on proppant erosion are required as there is still no consensus on the mechanism theory of erosion itself.

Credit author statement

Ainni Syuhada Ramlan: Conceptualisation, Writing - Original draft preparation; **Rohani Mohd Zin:** Conceptualisation, Funding acquisition, Supervision, Writing-Reviewing and Editing; **Noor Fitrah Abu Bakar:** Supervision, Writing-Reviewing and Editing; **Nur Hidayati Othman:** Writing-Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 14
CFD approach of erosion studies.

Approach	Description	Assumption	Advantage	Disadvantage	Application
Euler-Lagrangian	Fluid phase is treated as a continuum by solving the time-averaged Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles, bubbles, or droplets through the calculated flow field.	• The dispersed second phase occupies a low-volume fraction (less than 10%).	• Useful in prediction of the influence of the particles on the fluid flow (two-way coupling interactions) and particle-particle collisions and contacts (four-way coupling interactions).	• High computational demand. • Not suitable for high solid system except when coupled with DEM.	(Cheng et al., 2018); Li et al. (2005); Lu and Agrawal (2012)
Euler-Euler	Different phases are treated mathematically as interpenetrating continua.	• The sum of the volume fractions of the phases is equal to one. • A single pressure is shared by all phases.	• Faster result at lower cost in comparison with Euler-Lagrangian.	• Not suitable for low concentrated system.	Li et al. (2005); Kong and McAndrew, 2017)
Eulerian-Granular	Conceptual model where constitutive equations come from the particle interaction due to mean and fluctuation motion taking into account the particle-particle, particle-turbulence, fluid-particle, and particle to fluid effects.	• Uniform particle size.	• More realistic erosion prediction • Significant mitigation of the erosion wear in flow containing appreciable liquids and solids.	• High computational demand individual particle trajectory due to the averaging scheme. • The particle-wall interaction is not well captured.	(Lu and Agrawal, 2012, 2014); Tong and Mohanty (2016)

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Nomenclature

c_0	correction coefficient relating to k_f , dimensionless
C	constant related to the geometry of pore channels reflecting tortuosity
C_1	numerical constant for Kozeny-Carman equation, mD/m ²
C_2	empirical constant for SDR equation, mD/ms ²
d_r	sectional diameter of cylinder, mm
d_{50}	median diameter, mm
d_{90}	particle diameter at 90th percentile sieve analysis, mm
D	initial fracture aperture, mm
D_1	diameter of proppant, mm
D_2	thickness of coal bed, mm
D_{10}	effective diameter at which 10% of the particles are finer by weight
D_m	representative volume grain diameter, m
e	proppant pack void ratio
E_1	elastic modulus of proppant, MPa
E_2	elastic modulus of coal bed, Mpa
E_{Y1}	Young's modulus of the proppant, Gpa
E_{Y2}	Young's modulus of the rock, GPa
f_1	function related to the closure pressure, elastic modulus and Poisson's ratio of proppant, dimensionless
f_2	function related to the closure pressure, elastic modulus and Poisson's ratios of proppant and coal bed, dimensionless
F_{RCD}	fracture conductivity, $\mu\text{m}^2\cdot\text{cm}$
h	Width of fracture along the direction of closure pressure, cm
k	proppant pack permeability, mm
k_1	permeability 1, m ²
k_2	permeability 2, m ²
k_3	permeability 3, m ²
k_{KC}	Kozeny-Carman equation permeability, mD
k_{SDR}	Schlumberger Doll Research equation permeability, mD
k_f	fracture permeability, mm ²
k_{fp}	proppant pack permeability, mm ²
kW_f	fracture conductivity, $\mu\text{m}^2\text{cm}$
K_f	supported fracture permeability, μm^2
K_{fh}	fracture conductivity, $\mu\text{m}^2\cdot\text{cm}$
l_r	length of cylinder, mm
L	effective flow length, cm
m	porosity constant for SDR equation
n_1	number of proppants in each layer
n_2	number of proppant layers
N	number of proppants in the model
P	closure pressure, MPa
P_C	formation pressure, MPa
P_i	pressure at inlet (atm)
P_{SC}	pressure at standard condition
Q_{SC}	flow rate at standard condition
r	equivalent radius of the pore, cm
R	radius of the proppant, mm
R_{s1}	proppant distance ratio 1, dimensionless
R_{s2}	proppant distance ratio 2, dimensionless
t	production time after hydro-fracturing, in days
T	temperature at inlet (°R)
T_{2GM}	geometric mean of T_2 distribution, s
T_{SC}	temperature at standard condition
u_m	displacement of the un-contact point between the fracture and the proppant under closure pressure, mm
ν_1	Poisson's ratio of proppant, dimensionless
ν_2	Poisson's ratio of coal bed, dimensionless
w	fracture width
w'	slot width of the channel fracture, cm
w_f	fracture width, m

w_f	thickness of a proppant pack
w_{f0}	initial fracture width, mm
w_i	initial width of the proppant pack before differential stress is applied
w_s	width of the sandstone slab, cm
W	fracture aperture, m
X	initial fracture aperture, mm
z	gas compressibility factor

Greek letter

α	the change in the fracture aperture, mm
α'	change in distance between Cylinder 1 and plane, mm
α''	multilayer aperture change (one side), mm
β'''	multilayer deformation of cylinders (one side), mm
ε	axial strain
λ	aspect ratio of cylinder, dimensionless
μ	dynamic viscosity of the fluid, cp
η	crushing rate of the proppants, %
ϕ	fracture porosity under the closure pressure, %
Φ_0	initial porosity, dimensionless
$\varnothing$	total pack porosity, dimensionless
$\varnothing'_c$	the porosity of channel after proppant embedment, dimensionless
τ	tortuosity of the pore

For erosion

d_0	threshold particle size, μm
D	impact particle diameter, μm
D'	standard particle diameter
d	particle size, μm
E	erosion, mg/g
E_{90}	erosion damage at normal angle, $\text{mm}^3.\text{kg}^{-1}$
E_m	erosion wear per impacting particle, mg/g
E_v	erosion, cm^3g^{-1}
$\hat{E}_1$	primary erosion, mg/g
$\hat{E}_2$	secondary erosion, mg/g
ε_C	critical strain
ε_d	erosion ductility
$\Delta\varepsilon_m$	average strain
G	molecular weight of the target, g
$g(\alpha)$	impact angle dependence of normalised erosion
H_v	Vickers hardness values, 36 kg/mm^2
ΔH_m	enthalpy of melting of the target, $\text{cm}^{-2}\text{s}^{-2}$
K	constant
K_T	kinetic energy transferred from the impacting particles to the target per unit mass of particles, $\text{cm}^{-2}\text{s}^{-2}$
k	thermal conductivity of the target, $\text{g.cm.s}^{-3}.\text{K}^{-1}$
k_1	exponents determined by the properties of the particle (type of particle)
k_2	exponent determined both by the material hardness and by particle properties
k_3	exponents determined by the properties of the particle (type of particle)
L	plastic zone size
η	erosion efficiency, dimensionless
P	pressure
ρ_P	mass density, g.mm^{-3}
ρ_t	density of target material, kg/m^3
ρ_t	density, g.cm^{-3}
q	depth, mm
R	particle roundness, dimensionless
S	scaling factor, dimensionless
T_m	temperature of melting of the target, K
V	velocity, ft.s^{-1}
V_0	threshold velocity, ft.s^{-1}
V_r	test velocity, ft.s^{-1}
v	impact velocity, m.s^{-1}
v'	standard impact velocity
α	e impact angle, $^\circ$
σ	density

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